Proceedings of A Workshop on

INTELLIGENT TURBINE ENGINES FOR ARMY APPLICATIONS

held at the

Massachusetts Institute of Technology
Cambridge, MA 02139

March 21-22, 1994

Sponsored by
U.S. Army Research Office

WORKSHOP ON INTELLIGENT TURBINE ENGINES FOR ARMY APPLICATIONS

Day 1 - Monday, March 21, 1994

7:45	Registration
8:30	Welcome and Introduction – A. Epstein, MIT & D. Mann, ARO

Advanced Control for Gas Turbines: Industry and Government Perspective

9:00	Army View of Rotor Craft Turbine Engine Controls - Present & Future Applications – V. Edwards, Aviation R&D Engineering Center
9:30	Army Ground-Based Gas Turbine Engines – R. McClelland, USA Tank-Automotive Center
10:00	Experience and Potential for Advanced Engine Controls – J. Kulberg, Pratt & Whitney, E. Hartford
10:30	Break
10:50	Advanced Engine Control – S. Carpenter, GE Aircraft Engines
11:20	NASA Research in Engine Control – W. Merrill, NASA Lewis Research Center
11:50-13:00	Lunch

Overview of Active Control in Gas Turbine Engines

13:00	The Promise of Active Control for Helicopter and Tank Engines – A. Sehra, Textron Lycoming
13:30	MIT Research in Active Compressor Stabilization – J. Paduano, MIT
14:00	GE Research in Active Control – A. Spang, GE Research Center
14:30	Break
14:50	Progress in Modeling & Control of Compressor Stall – C. Nett, UTRC
15:20	A Systems Study of the Impact of Active Compressor Stabilization – K. Tow, GE Aircraft Engines, Lynn
16:00	Tour of MIT Gas Turbine Laboratory, Active Control Facilities
18:30	Dinner

Day 2 - Tuesday, March 22, 1994

8:30	Panel Discussion on Intelligent Engine Control – Industry-Government-Academia
9:30	Change to Breakout Panels
9:45-12:00	Breakout Discussions a) Engine Systems & Applications b) Components c) Control Theory
12:00	Lunch
13:00	Reports from the Breakout Panels Open Discussion
14:30	Closing Remarks - ARO Interests in Intelligent Engines – D. Mann, ARO
15:00	Adjourn

REPORT DOCUMENTATION PAGE

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13. ABSTRACT *(Maximum 200 words)*

This report documents the proceedings of a workshop on Intelligent Turbine Engines for Army Applications held at the Massachusetts Institute of Technology on March 21-22, 1994. The workshop brought together experts from government, industry, and academia to explore ways in which advanced controls concepts can be used to significantly benefit Army gas turbine engines. Participants discussed Army control related requirements. Emphasis was placed on the integration of active control into helicopter and ground vehicle gas turbines.

14. SUBJECT TERMS

Gas turbines, active control and control

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March 21-22, 1994
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SUMMARY VIEWGRAPHS OF BREAKOUT PANELS

(Parenthetical remarks are those of the Editor)

Vehicle Systems & Components Panel

SYSTEMS

Risk	Potential Reward	
L	H	• Identify active control benefit to small engines vs. large engines • Diagnostics – condition-based maintenance
M	H	• New sensor / actuator systems • Reconfigurable smart engine (For battle damage component failure)
H	H	• Simplicity (Of active control system) • Passive control (Same dynamic behavior without computer actuators) • Totally Silent engine
M	M	• Active avoidance of distortion (Manipulate inflow to engine) • Active control of inlets
L	L	• Integration – adaptive propulsion control (Integration of helicopter flight & propulsion controls)

L = Low, M = Medium, H = High

Vehicle Systems & Components Panel

COMPONENTS

Risk	Potential Reward	
H	H	• Active blade control – shape, flutter, forced vibration damping • Active combustion control – Emissions – Pattern factor – Life cycle cost • Tip clearance control (Now done open loop in large engines) • Active control of separation • High lift / max lift airfoil
L	M	• Optimized turbine cooling / performance (Control of turbine cooling)
H	M	• Katzmeier effect – unsteady blading (Unsteady lift would increase loading capability)

Vehicle Systems & Components Panel

PROCESS

Risk	Potential Reward	
L	H	• System identification (Of fluid & structure dynamics) • Identify low hanging fruit beyond compressor stability – Risk vs. reward • Strategy for technology insertion • Multidisciplinary w/ in-depth teams
M	H	• Stall line prediction - accurate – Passive – With active control
H	H	• Active control of flutter
L	M	• Active control as a demo tool
L	L	• Active control of surge only – Not including rotating stall
L	H	• Inverse optimization technique – Better modelling
Generic		• Closed loop control of unsteady flow

Control Panel Summary

ENGINE CONTROL USING "CONVENTIONAL" ACTUATORS/SENSORS

- Nonlinear control (NL) techniques are needed – CONTEXT is very important
- To understand the "class" of NL systems, a standardized NL model structure for engines, similar to the flight dynamics standard
  - Must involve industry
  - Recognize noise and NL
  - Be flexible (for inclusion of new concepts)
  - Be built around experimental testbed
- Wish list – a testbed with complexity/dynamics between: a simple compressor rig and engine
- Airframe/engine integration in helicopters
  - Situation awareness/feedforward
  - Rotor aerodynamics in transient maneuvers
  - Performance seeking in new context
    - Vibration as well as fuel burn
    - Rotor speed as variable
  - Hardware/know-how is ripe

Control Panel Summary (Cont.)

- Recognition
  - Use of control theory relies on context
- Recommendations depend on context of fruitful work to be done
- Unsteady fluid mechanics
  - New system identification tools for fluid systems
    - Noise environment far worse
    - Techniques from fluid theory should be exploited
      - Length scale, time scale concepts
      - Ensemble averaging
  - Converting distributed fluids model to control form
    - Many structural dynamic, nonlinear dynamics techniques available
    - CFD to ODE } Create low order
    - PDE to ODE } aggregate models
  - Collaboration with experiments is vital

Control Panel Summary (Cont.)

- Other nonlinear control issues
  - Multivariable mode selection
  - Transient performance improvement through NL control
    - How to measure, insure safety during design
  - Engine companies should <u>talk to</u> academia about their problems
  - Disturbance rejection
    - Characterizing disturbances/uncertainty/ noise

- Advanced concepts
  - Sponsoring organizations should explicitly fund control work which <u>collaborates</u> with <u>experimental application</u>

SPEAKERS' PRESENTATIONS

WORKSHOP
ON
INTELLIGENT TURBINE ENGINES

DAVID M. MANN
ARMY RESEARCH OFFICE

21-22 MARCH 1994
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

INTELLIGENT TURBINE ENGINES

MOTIVATION

Reduced Fuel Consumption

Example: Mechanized Infantry Division

58 M1 tanks, 21 Attack helicopters

Fuel use: 673,000 gal/day

Reduced Volume/Increased Power

Faster Deployment

Increased Range/Payload

Improved Reliability

Reconfigurable/Adaptable

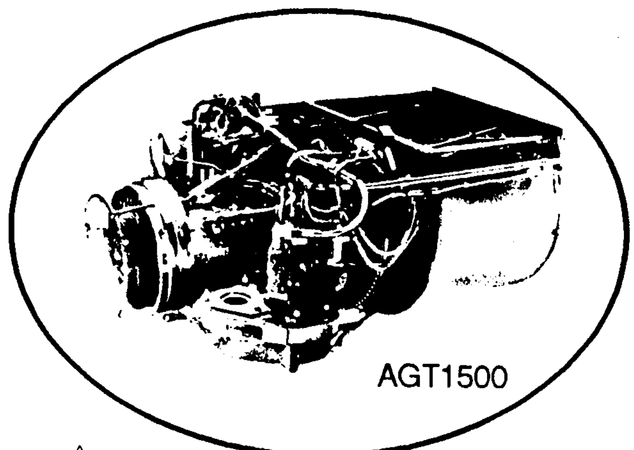
INTELLIGENT TURBINE ENGINES

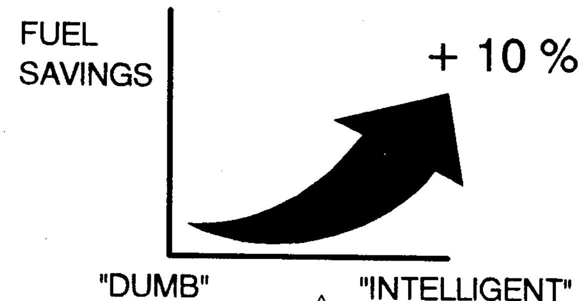
Application of Artificial Intelligence-based Advanced Control Strategies to Gas Turbine Engines for Improved Economy and Reliability

AI ALGORITHMS
- Fuzzy Logic
- Genetic Algorithms
- Rule-based Control
- Model-based Control
- Hybird Systems

ENGINE MODELS
- Turboshaft
- Simple (T-800)
- Recouperated (AGT-1500)

CONTROL METHODOLOGY
- Diagnostics/Prognostics
- Adaptive Reconfiguration
- Optimization





APPLICATIONS
- Tanks
- Rotorcraft
- Civilian Aircraft

WORKSHOP ON INTELLIGENT TURBINE ENGINES

<u>PRODUCTS</u>

Assessment of current status

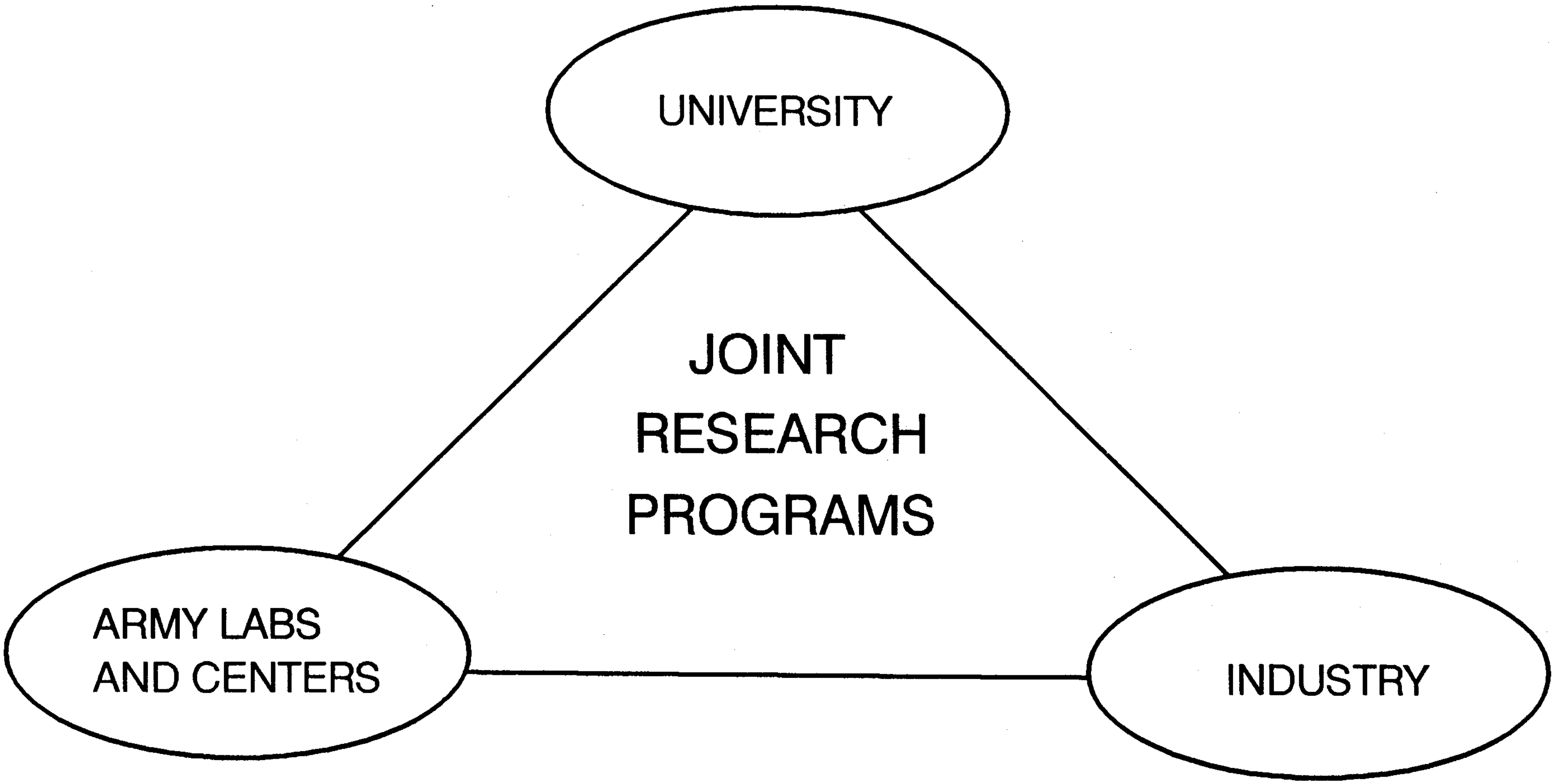
Identification of opportunities

Identification of enabling technologies

Identification of basic research requirements

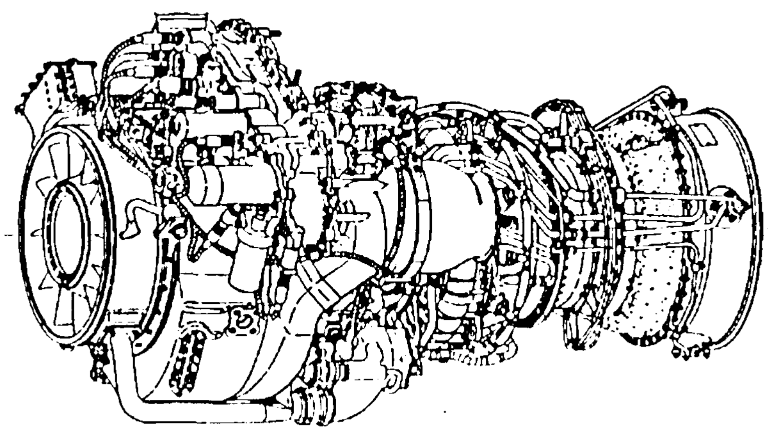
A NEW RESEARCH PARADIGM

A University-Army-Industry Partnership for Research



ARO WILL FACILITATE THE PARTNERSHIP WITH SUPPORT AND COORDINATION

INTELLIGENT TURBINE ENGINE WORKSHOP



FOR ARMY APPLICATIONS

VERNON R. EDWARDS
CHIEF, PROPULSION
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ATCOM

ARMY VIEW OF ROTORCRAFT TURBINE CONTROLS PRESENT AND FUTURE CONSIDERATIONS

o CURRENT ARMY FLEET HAS DIVERSITY OF TECHNOLOGIES
- UH-1/T53 FLY BALL GOVERNOR
- MH-47E/T55 FULL AUTHORITY DIGITAL ELEC CONTROL
- DIAGNOSTICS HUMAN DEPENDENT
- HISTORY RECORDING AND VARIOUS DEGREES OF FAULT MONITORING

o ARMY'S MOST MODERN SYSTEMS
- UH-60/T700 & AH-64/T700 HYDROMECHANICAL *SUPERVISORY* DIGITAL ELECTRONIC CONTROL
- OH-58/250C30R PNEUMATIC-MECHANICAL *SUPERVISORY* DIGITAL ELECTRONIC CONTROL
- MH-47E/T55 FADEC

ARMY VIEW OF ROTORCRAFT TURBINE CONTROLS PRESENT AND FUTURE CONSIDERATIONS

o TYPICAL CURRENT TECHNOLOGY CAPABILITIES

- ISOCHRONOUS POWER TURBINE GOVERNING
- TORQUE MATCHING IN MULTI-ENGINE APPLICATIONS
- TEMPERATURE LIMITING/START OVER TEMP ABORT
- OVERSPEED PROTECTION
- RUDIMENTARY SURGE RECOGNITION/AVOIDANCE
- FLIGHT CONTROL ANTICIPATION (COLLECTIVE)
- AUTOMATIC START/RELIGHT CAPABILITY
- NOTCH FILTER FOR TORSIONAL STABILITY
- TORQUE RATE ATTENUATION (UNCOMPENSATED)

TYPICAL PROBLEMS & SHORTCOMINGS

o ENGINE/DRIVE TRAIN/AIRFRAME INTERACTIONS

  - T0RSIONAL MODE OSCILLATIONS
  - TRANSIENT ROTOR DROOP
  - TORQUE SPLITTING
  - TORQUE PREDICTABILITY

o UNABLE TO AUTOMATICALLY MANAGE FAILURE MODES

o NO ANTICIPATION FOR UNCOMPENSATED INPUTS

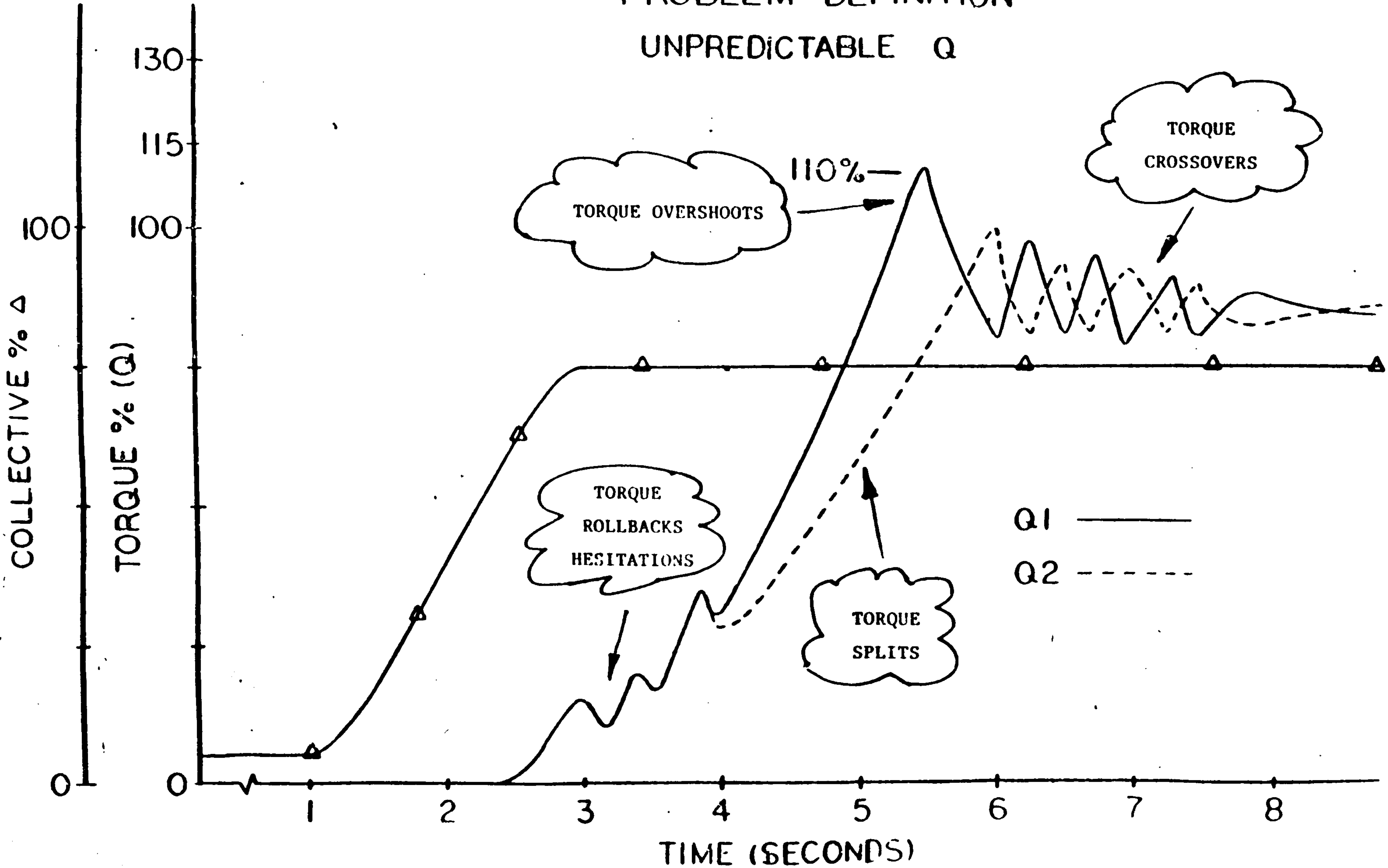
o LIMITED ADAPTIVE CAPABILITIES (ENG/OPER CONDITIONS)

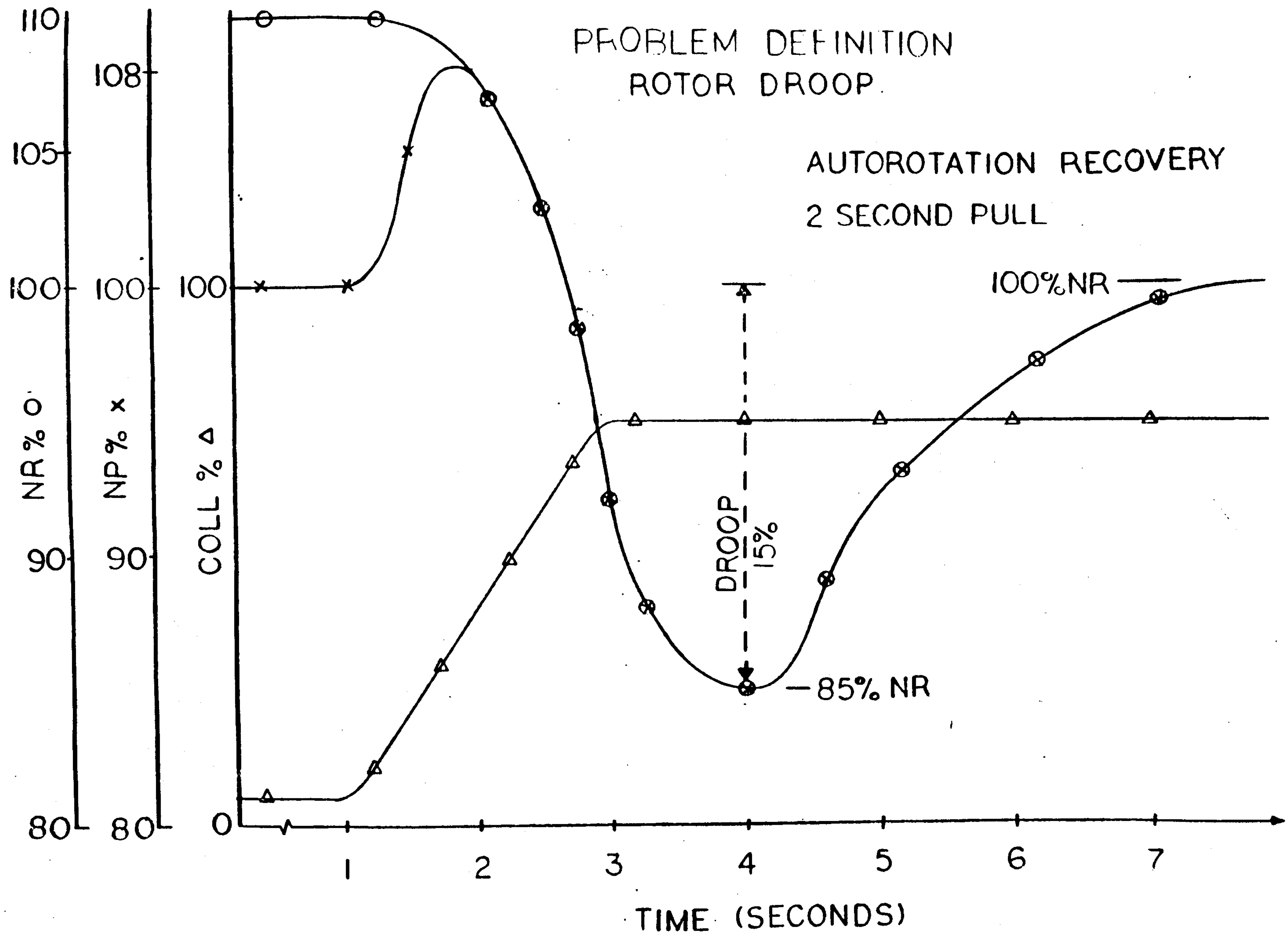
o UNABLE TO SELF-DIAGNOSE ENGINE HEALTH
NO PROGNOSTICS

o EXTENSIVE FLT TEST TO OPTIMIZE EACH INSTALLATION

PROBLEM DEFINITION

UNPREDICTABLE Q



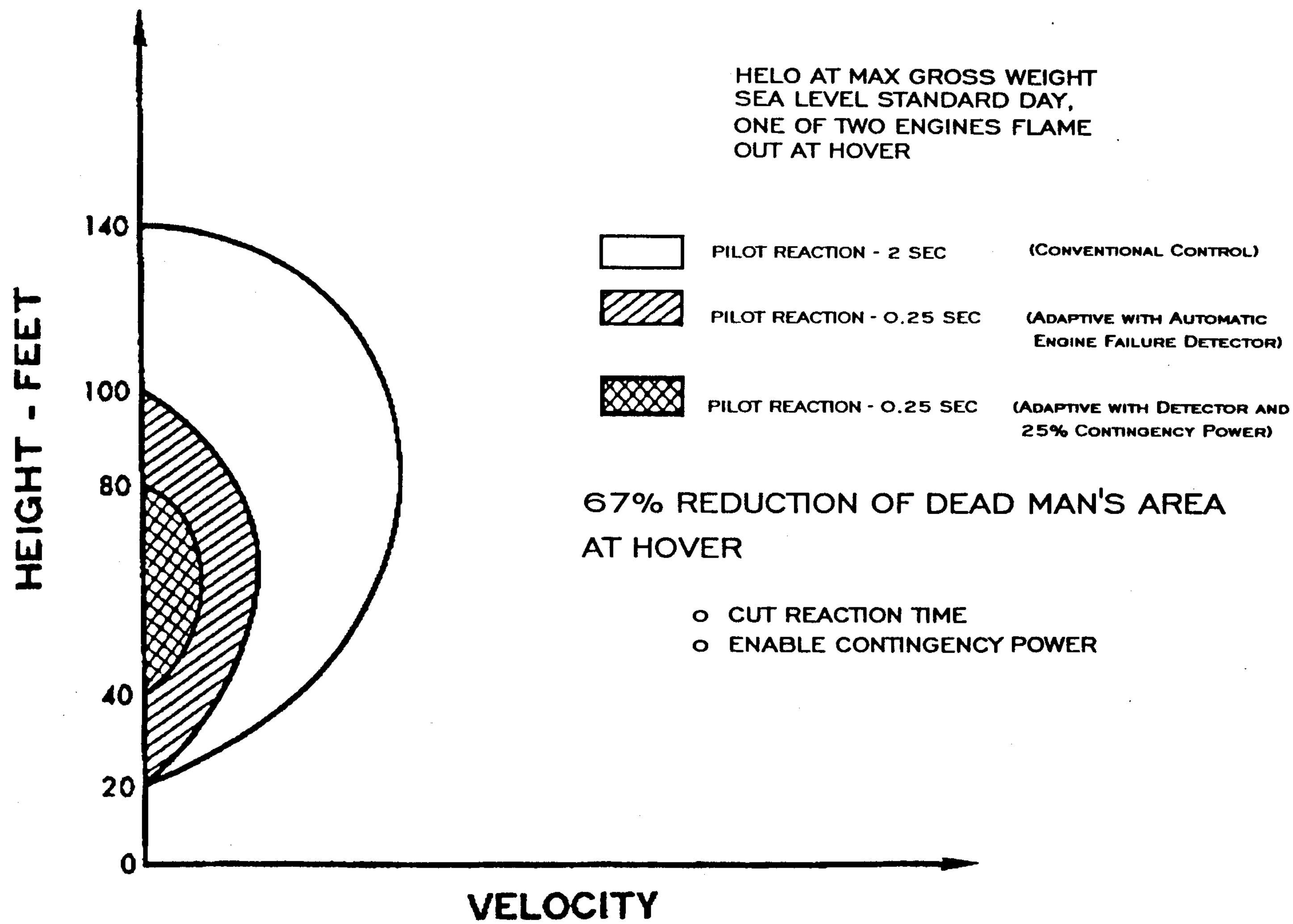


PROBLEM DEFINITION
ROTOR DROOP
AUTOROTATION RECOVERY
2 SECOND PULL
100%NR
DROOP
15%
85% NR
NR % o
NP % x
COLL % ∆
110
105
100
90
80
108
100
90
80
100
0
1
2
3
4
5
6
7
TIME (SECONDS)

INTELLIGENT ENGINE & CONTROL OPPORTUNITIES

- HI-FIDELITY *TOTAL* SYSTEM SIMULATION
- RECONFIGURABLE CONTROL LOGIC
- FAIL SMART, RAPID IDENT & AUTO SELECT BASED ON SYSTEM PARAMETERS
- TRANSPARENT FAULT/FAILURE DETECTION/RECOVERY TO ALLOW CONTINUED MISSION CAPABILITY
- ADAPTABILITY TO DEGRADED OPERATING CONDITIONS
- OPTIMIZE ROTORCRAFT PERFORMANCE - SELF TUNING/PERFORMANCE SEEKING CONTROLS
- SELF DIAGNOSIS FOR ALL ON-BOARD ENGINE SYSTEMS & INTERFACES
- *CONSIDER* INTEGRATED FLIGHT & ENGINE CONTROLS

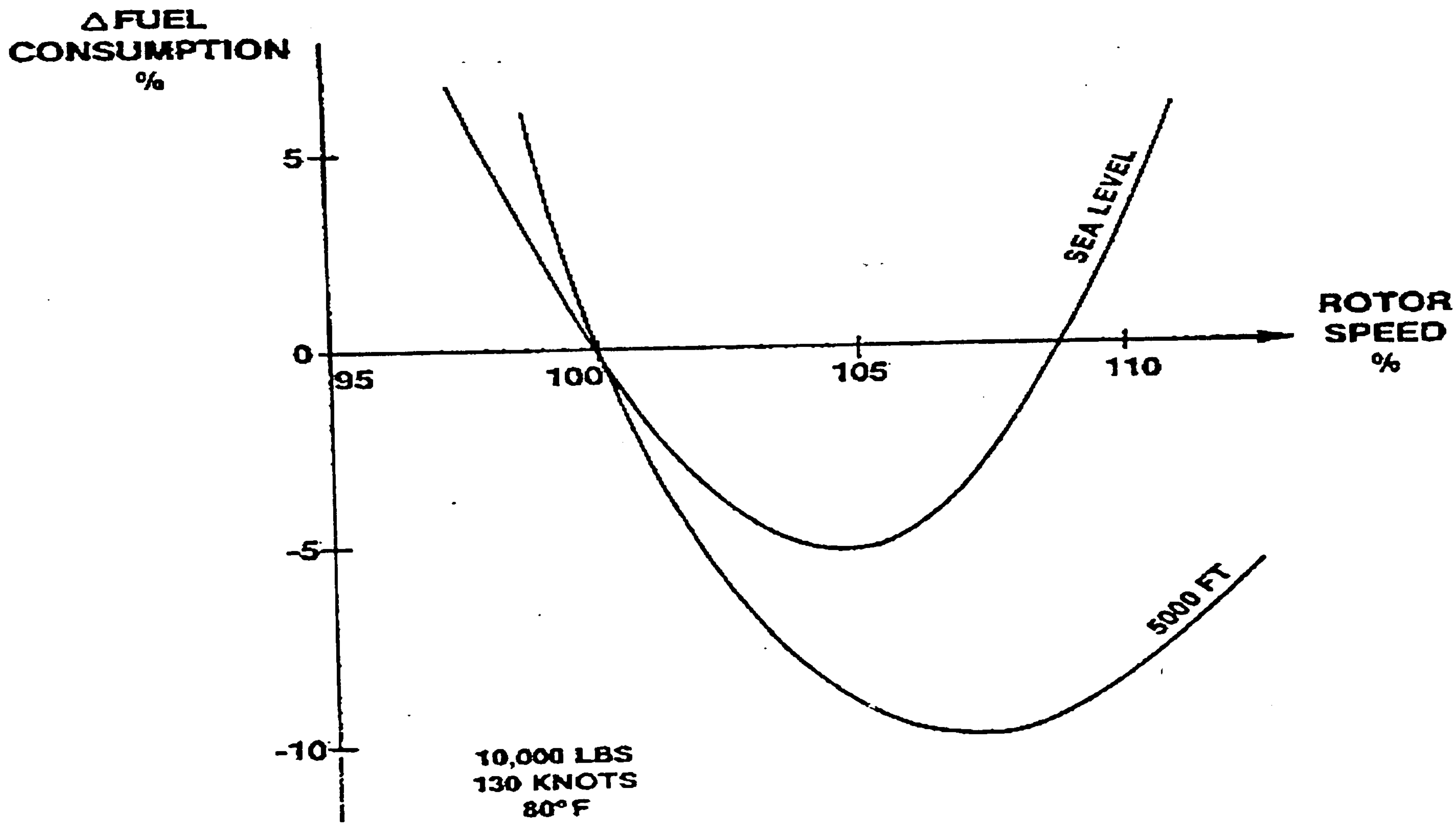
POWER LOSS SURVIVABILITY



67% REDUCTION OF DEAD MAN'S AREA AT HOVER

- CUT REACTION TIME
- ENABLE CONTINGENCY POWER

ENGINE RELATED CONCEPTS
MINIMUM FUEL CONSUMPTION



- OPERATE ROTOR AT OTHER THAN 100% SPEED
- SEARCH OUT OPTIMUM SPEED

SUMMARY OF EXPECTED BENEFITS

o ENHANCED FLIGHT SAFETY

o ENHANCED ROTORCRAFT SYSTEM PERFORMANCE

o REDUCED LIFE CYCLE COST
  - REDUCED ANNUAL O & S COSTS
  - IMPROVED ENGINE OPERATION
  - REDUCED ENGINE MISHAPS

o REDUCED PILOT WORK LOAD

o IMPROVED MAINTAINABILITY & DIAGNOSTIC CAPABILITY

ARMY GROUND-BASED GAS TURBINE ENGINES

BY
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U.S. ARMY, TACOM

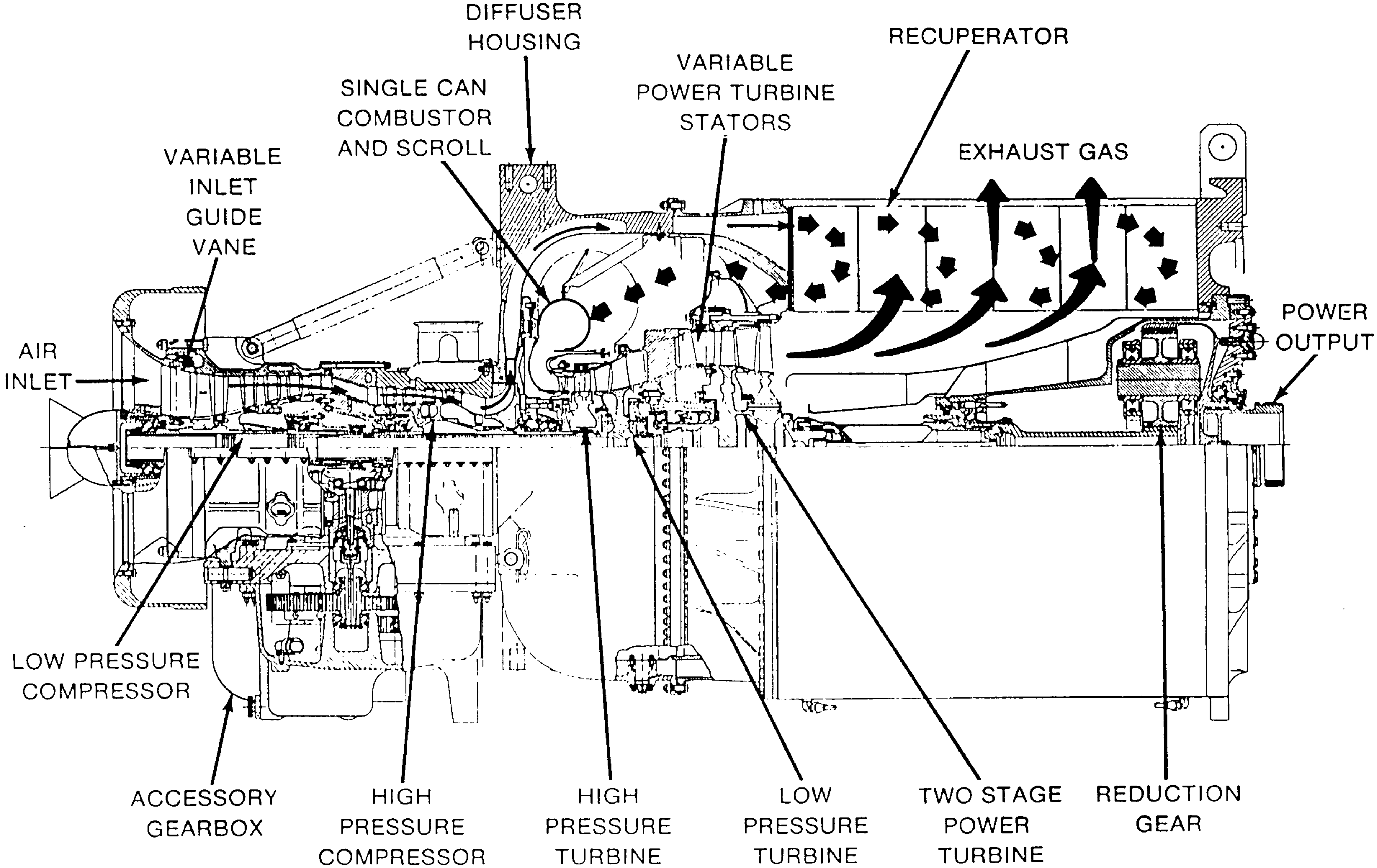
ARMY/N.G. GROUND VEHICLE INVENTORY

Vehicle	QTY Army	QTY N.G.	Engine Model	Manufacturer	HP
			TRACKED VEHICLES		
M60 Fam	1190	66	AVDS-1790	TCM	750
M728 CEV	728	89	AVDS-1790	TCM	750
M88 MRV	1560	697	AVDS-1790	TCM	750
M1	5841	2246	AGT-1500	Textron/Lycoming	1500
M2/3	5488	957	VTA-903T	Cummins	600
M113	27,416	10,071	6V-53T	Detroit Diesel	275
M9ACE	430	18	V - 903	Cummins	295
M551	1070	0	6V-53T	Detroit Diesel	300
M109	4000	0	8V-71T	Detroit Diesel	405
			WHEELED VEHICLES		
HET	749		8V92TA	Detroit Diesel	430
HEMTT	9663	2632	8V92TA	Detroit Diesel	445
PLS	120		8V92TA	Detroit Diesel	500
M35A2	44058		LDT-465-1D	Hercules	140
FMTV	0		3116	CAT	225
M809	15850		NH 250	Cummins	250
M939	11414	2507	6CTA8.3	Cummins	240
M880	2655		318 (Gas)	Chrysler	140
HMMWV	79000		GM6.2	GM	150
CUCV	35653	20205	GM6.2	GM	150
M915 Fam	4099		NTC 400	Cummins	400
M915 A1/A2	3252		Series 60	Detroit Diesel	400

GROUND VEHICLE GAS TURBINE ENGINES

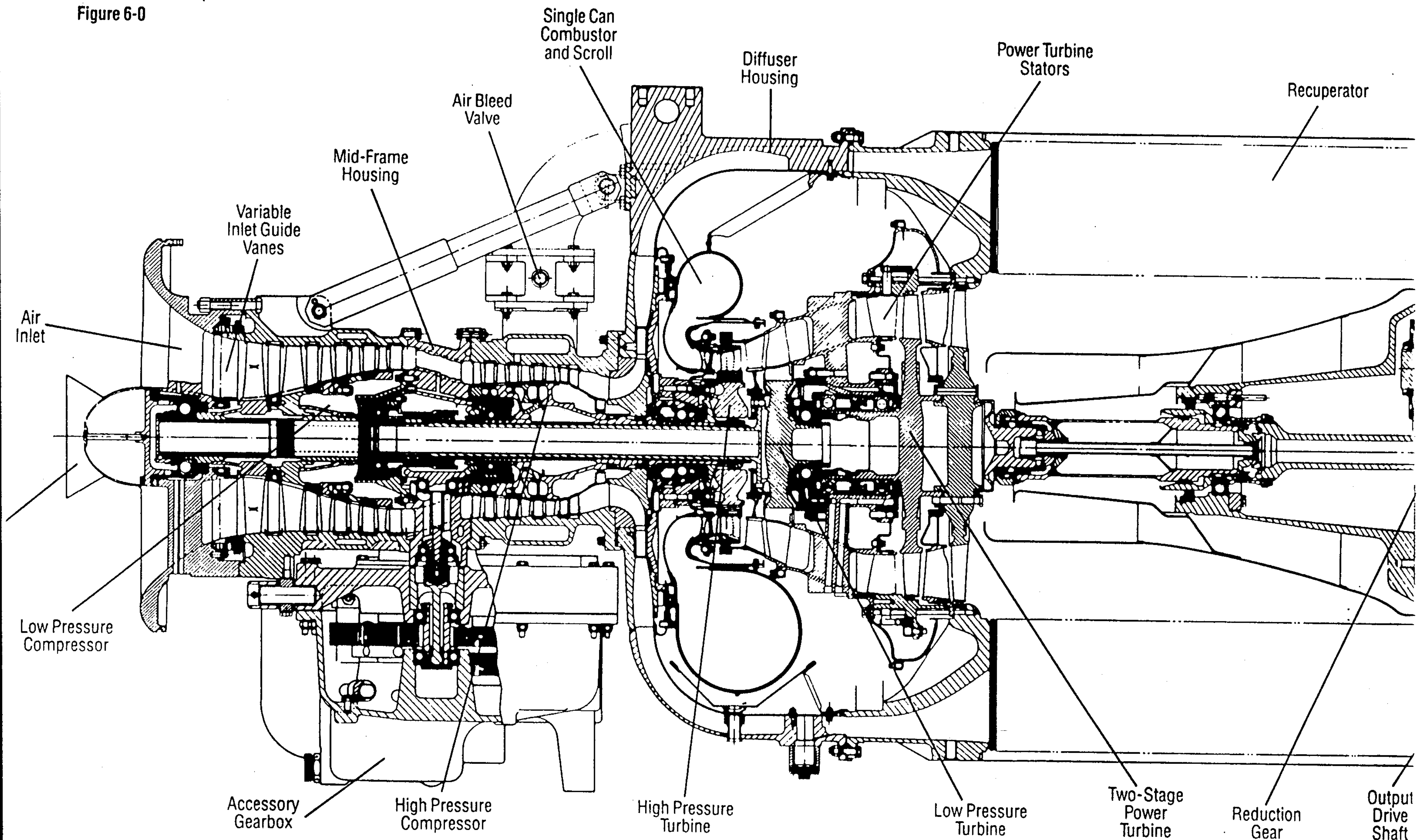
- AGT 1500
- LV 100

AGT 1500 CONFIGURATION



AVCO LYCOMING DIVISION
STRATFORD, CONN.

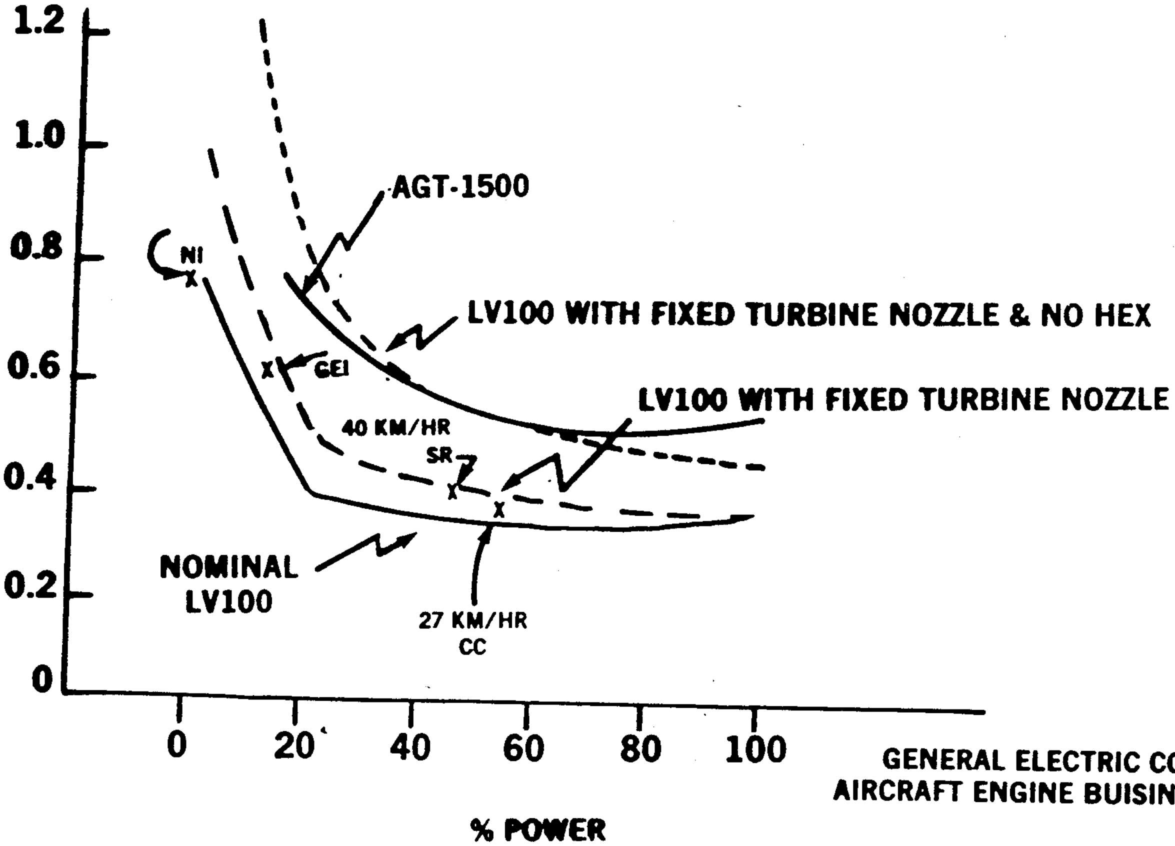
Main Internal Components
Figure 6-0



AGT1500 AND LV100 FEATURES

	AGT1500	LV100
PRESSURE RATIO	14:1	12:1
AIR INDUCTION RATR(LB/SEC)	12.5	7.5
BSFC (LB/BRAKE HP HR)	0.5	0.4
IDLE FUEL ECONOMY(LB/HR)	33	74
TIT (0 F)	2180	2470

LV100 VERSUS AGT 1500 SFC CHARACTERISTICS

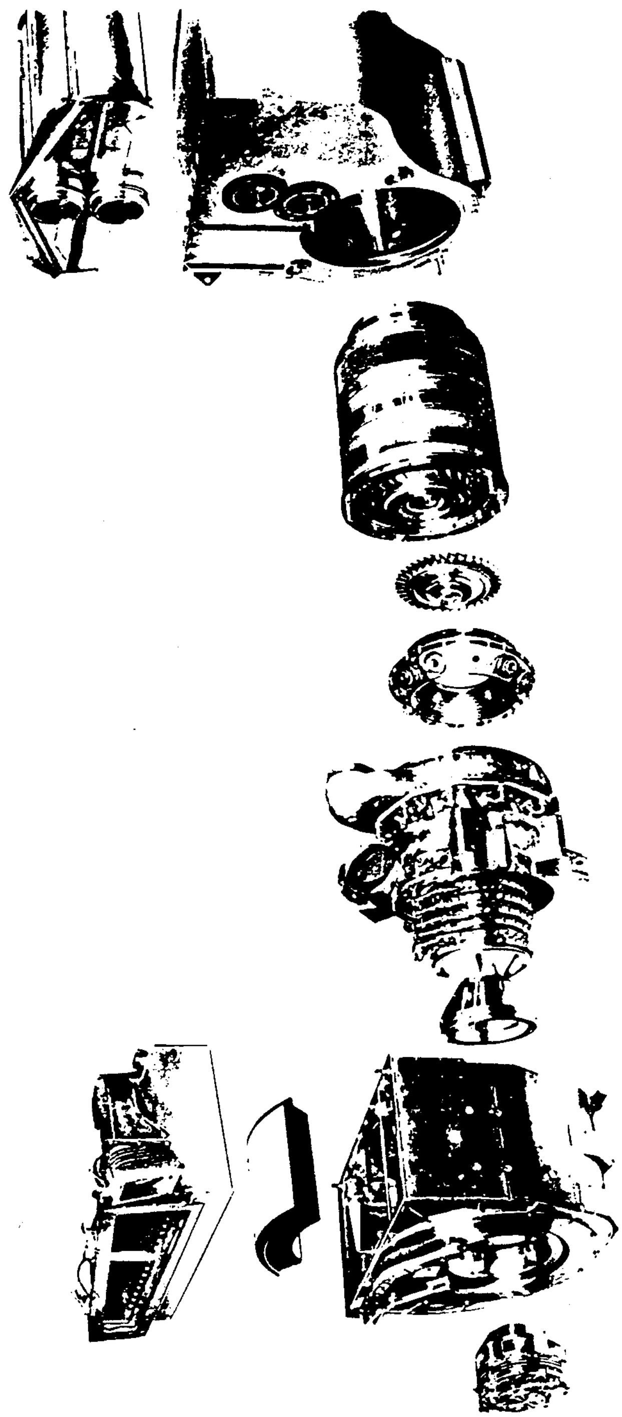


GENERAL ELECTRIC COMPANY
AIRCRAFT ENGINE BUISINESS GROUP

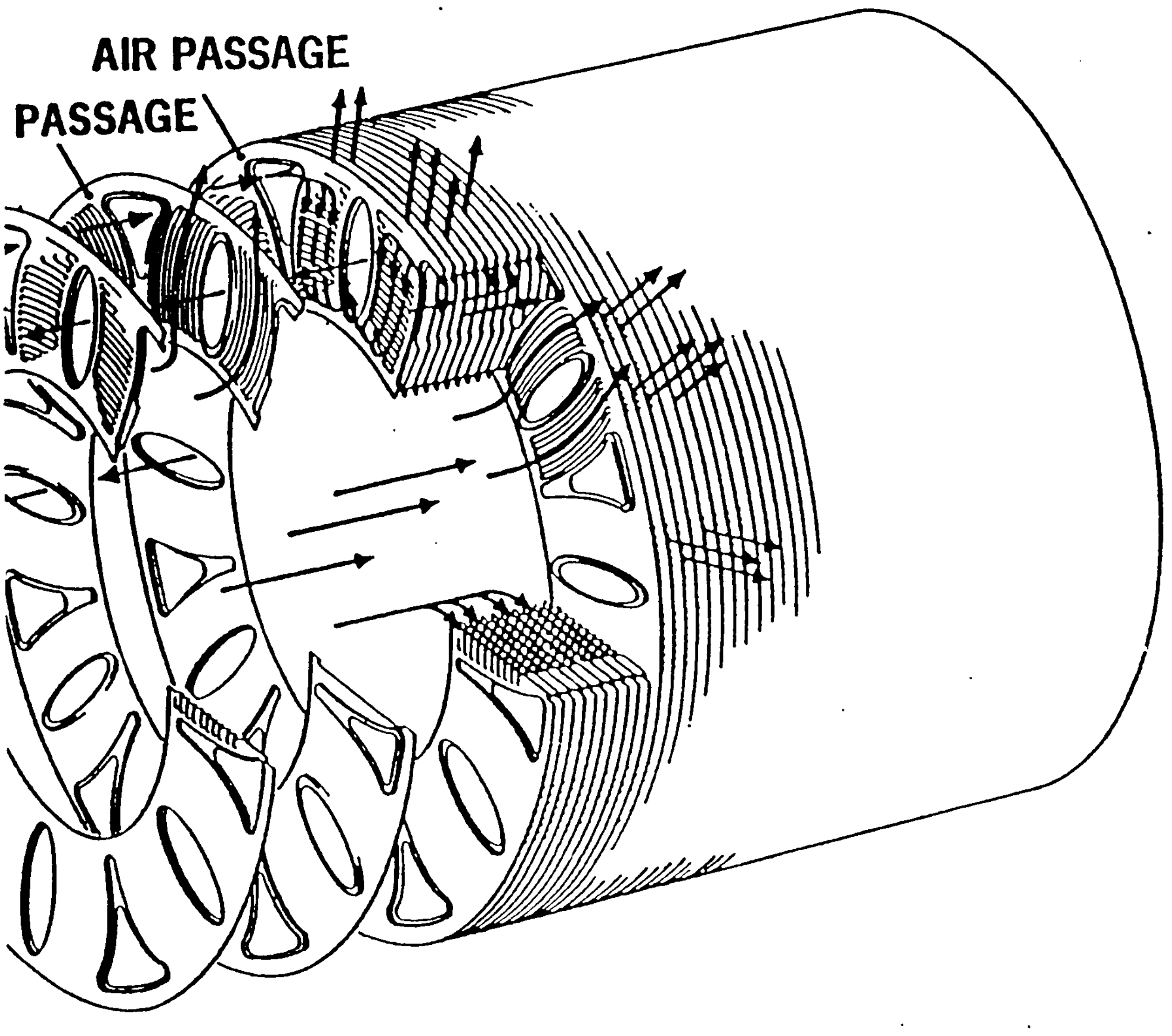
TAC-1450

GROUND VEHICLE ENGINE FEATURES

- AIR FILTRATION
- MODULAR DESIGN
- RECUPERATION
- IDLE FUEL ECONOMY



REGENERATOR SCHEMATIC



TANK ENGINE REQUIREMENTS

- POWER DENSITY
- FUEL ECONOMY
- MULTI FUEL OPERATION
- SIGNATURES
- ENVIRONMENTAL TOLERANCE
- RUGGED DESIGN- SOLDIER PROOF

ENGINE PERFORMANCE REQUIREMENTS

- QUICK ACCELERATION
- MAX SPEED CAPABILITY
- SPEED ON GRADE CAPABILITY
- POWER AT HIGH ALTITUDE

AGT1500 AND LV100 ENGINES

	AGT1500	LV100
DEVELOPER	TEXTRON	GE/TEXTRON
POWER (HP)	1500	1500
VOLUME (CU.FT)	31	25
PROP SYS VOL(CU FT)	291	175
PROP SYS WT(LB)	15191	12696
BFD FUEL (GAL)	500	300
SPROCKET POWER(HP)	950	1050

TANK ENGINE ELECTRONIC CONTROLLERS

VEHICLE-ENGINE	CONTROLLER
M1A1-AGT1500	ECU
M1A2-AGT1500	DECU
FUTURE-LV100	FADEC

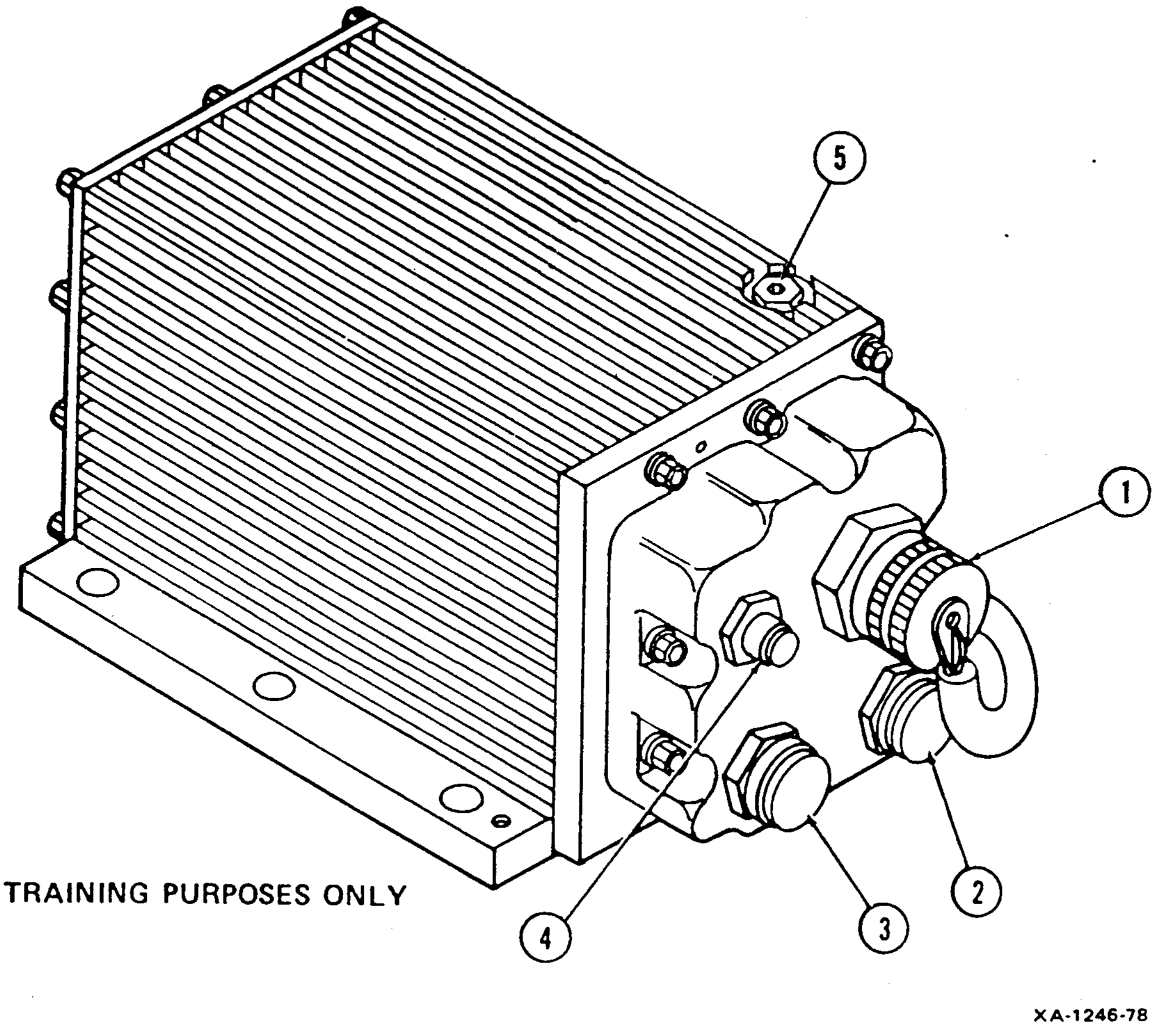


FIGURE 6-4. ELECTRONIC CONTROL UNIT

CONCLUSIONS

- VOLUME 40% LESS
- WEIGHT 16% LESS
- BFD FUEL 40% LESS
- SPROCKET POWER 11% MORE
- USER FRIENDLY VEHICLE
- IMPROVEMENTS IN PROGNASTIC AND DIAGNOSTICS
- IMPROVED RAM-D 70% HIGHER
- CONTROLS PLAY A SIGNIFICANT ROLE IN ALL THESE

ELECTRONIC CONTROL SYSTEMS FOR AIRCRAFT TURBINE ENGINES

- EXPERIENCE
- POTENTIAL

INTELLIGENT TURBINE ENGINES FOR ARMY APPLICATIONS
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
MARCH 21, 1994

Joel F. Kuhlberg

CHRONOLOGY

1980 - PW2037 ENGINE

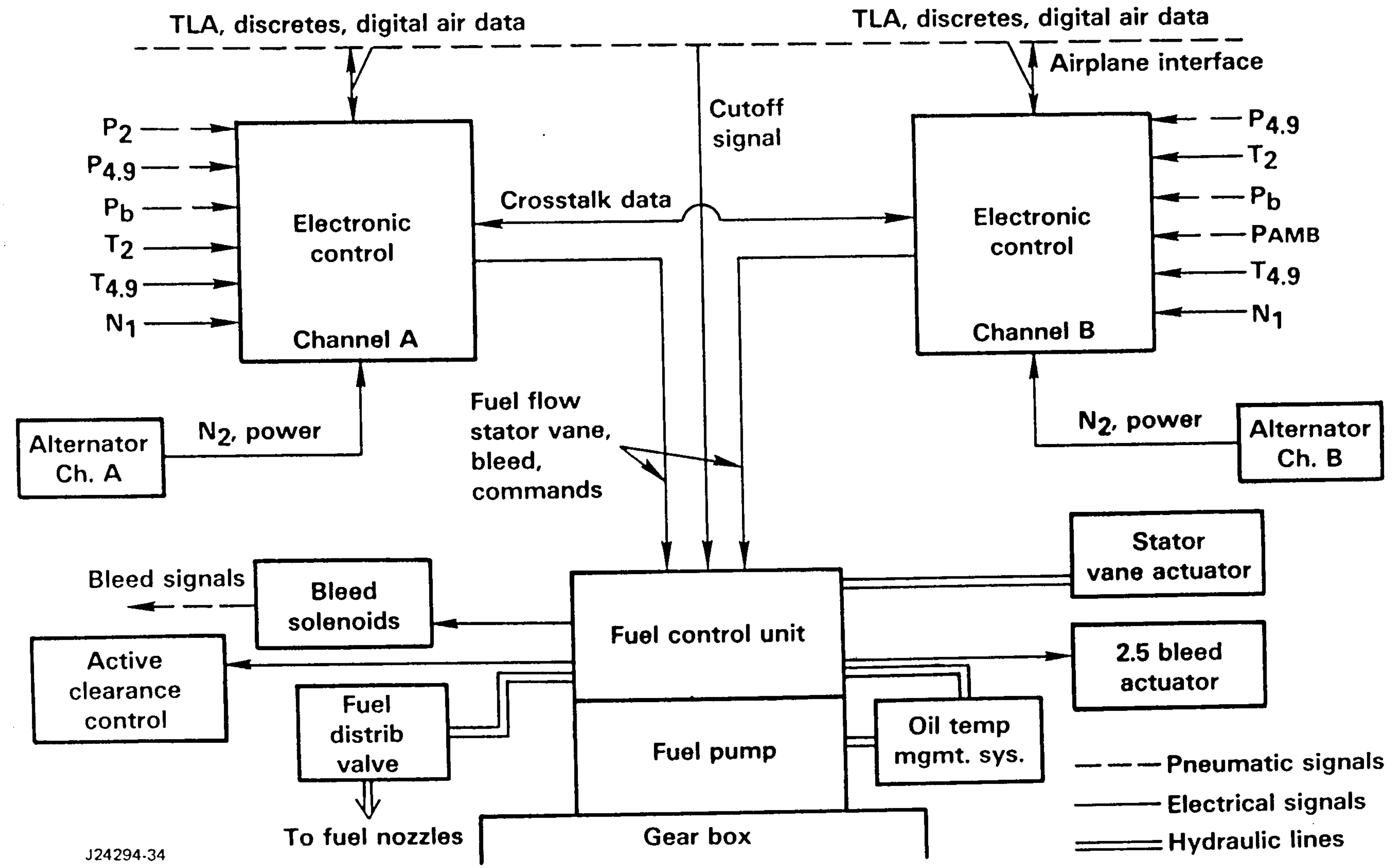
1994 - PW4084 ENGINE

2000 - ADVANCED ENGINE

ADVANTAGES OF FULL AUTHORITY ELECTRONIC ENGINE CONTROL

- REDUCTION IN FUEL BURN
- IMPROVEMENT IN CONTROL OPERATIONAL RELIABILITY
- REDUCTION IN WEIGHT
- REDUCTION IN CONTROL MAINTENANCE COSTS
- SIMPLIFIED COCKPIT PROCEDURES

PW2037 CONTROL SYSTEM — FUNCTIONAL CONFIGURATION



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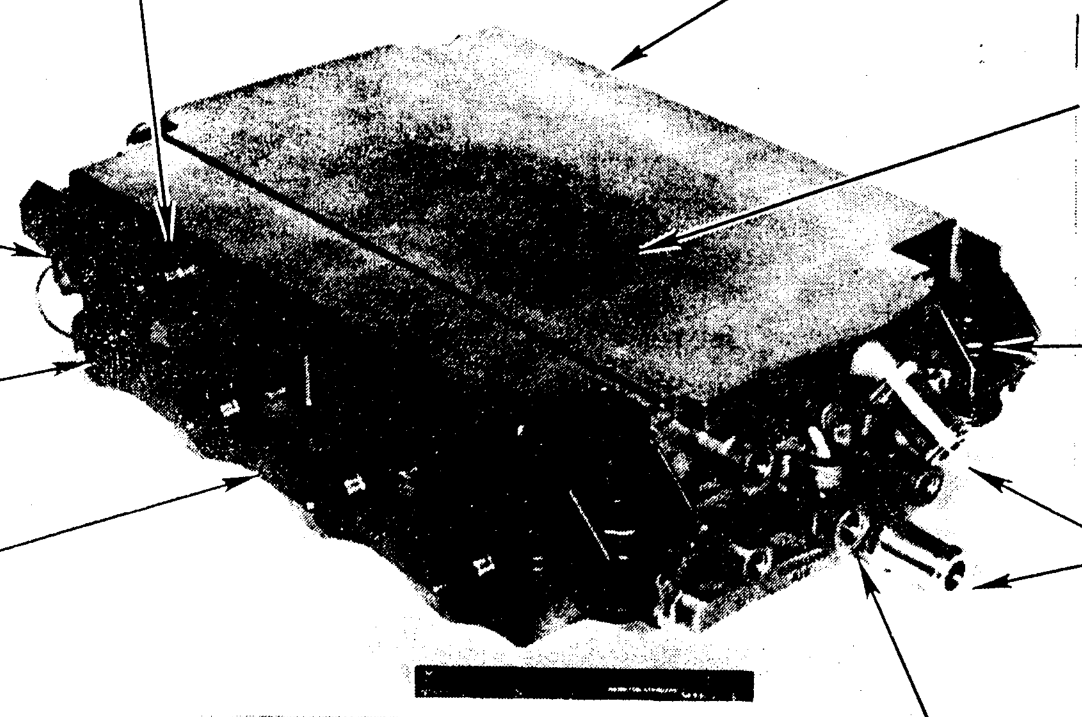
ELECTRONIC ENGINE CONTROL FEATURES

- MAINTAIN FIXED ENGINE RATINGS AT UNIQUE THROTTLE POSITIONS
- PROVIDE CONSTANT IDLE SPEED CONTROL
- PROVIDE ACCELERATION AND DECELERATION CONTROL
- PROVIDE ENGINE STARTING CAPABILITY
- PROVIDE ENGINE OVERSPEED AND OVERPRESSURE LIMITING
- POSITION HIGH COMPRESSOR VARIABLE STATOR VANES

ELECTRONIC ENGINE CONTROL FEATURES (CONTINUED)

- CONTROL COMPRESSOR BLEED AIRFLOW
- PROVIDE ACTIVE CLEARANCE AIRFLOW CONTROL AND TURBINE COOLING AIR CONTROL
- MODULATE OIL COOLER AIRFLOW
- PROVIDE THRUST REVERSER CONTROL AND THROTTLE INTERLOCK
- PROVIDE ENGINE PERFORMANCE DATA TO COCKPIT DISPLAYS AND CONDITION MONITORING SYSTEMS

ELECTRONIC ENGINE CONTROL



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ELECTRONIC CONTROL SYSTEM EXPERIENCE
1984 - 1994
13 AIRPLANE MODELS
15 MILLION HOURS

<u>HIGHS</u>

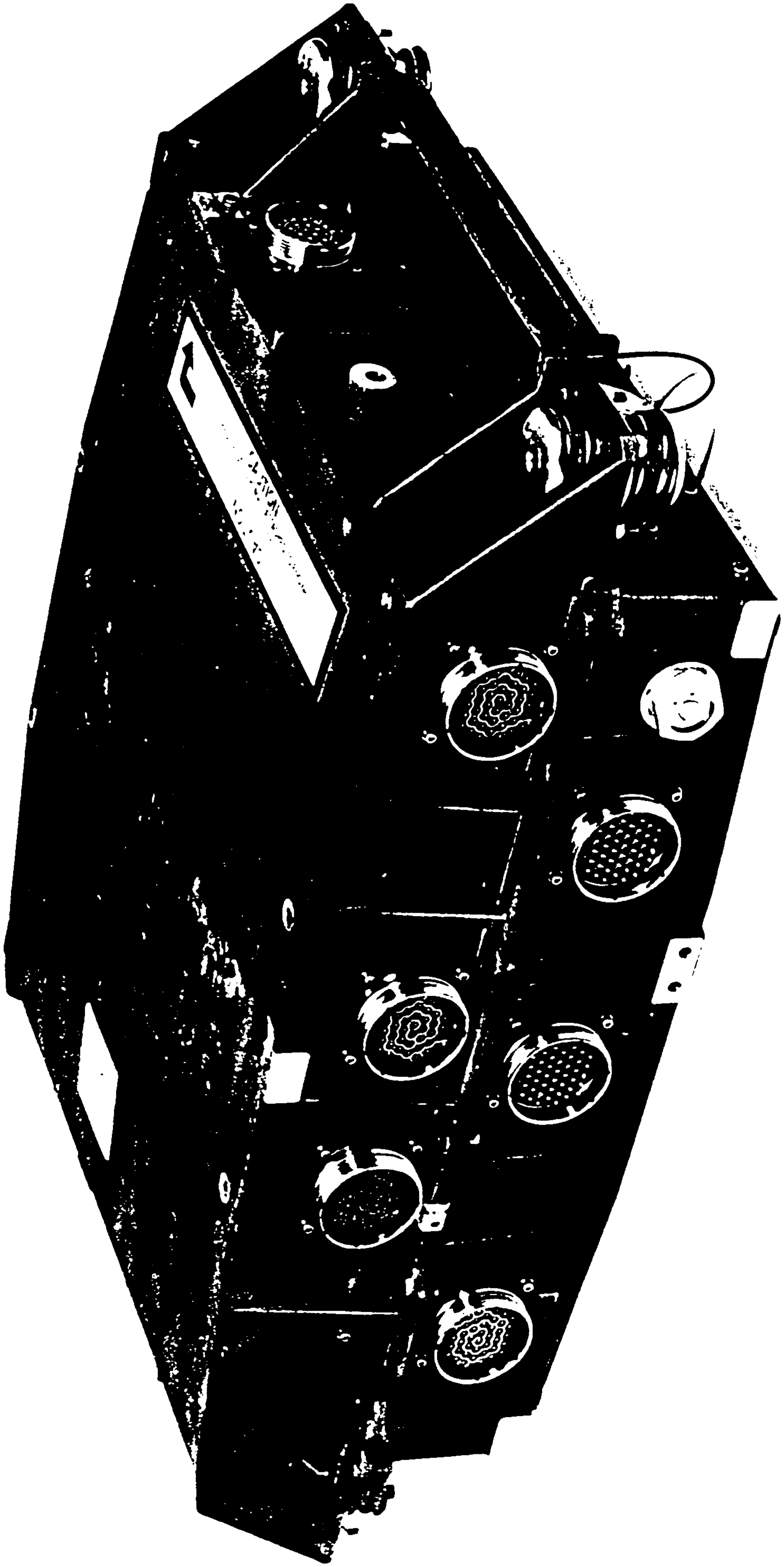
- RELIABILITY
- ROBUST SOFTWARE

<u>LOWS</u>

- WIRING
- VIBRATION
- NUISANCE MESSAGES

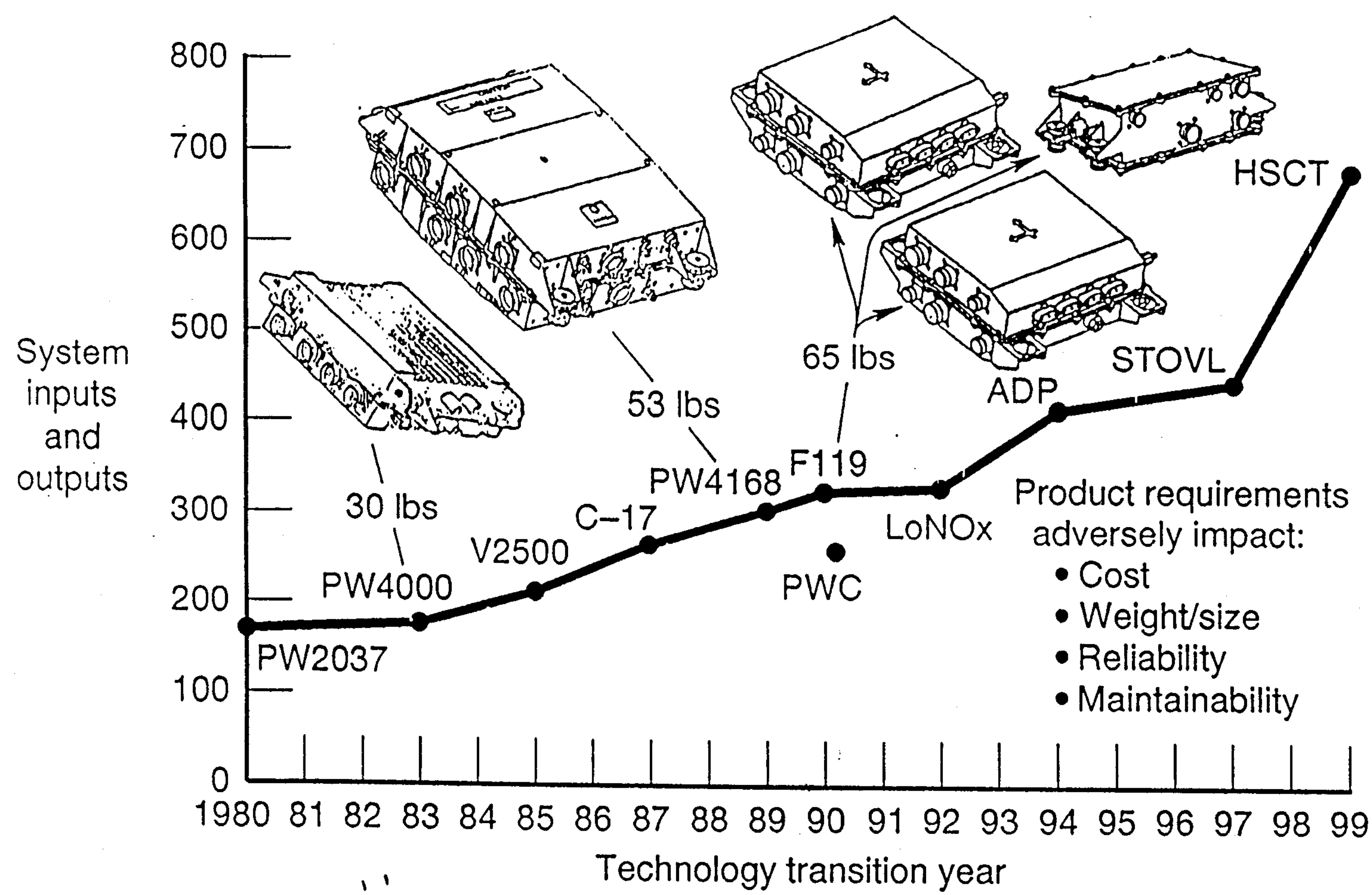
PW4000 FADEC FUNCTIONAL COMPARISON

FUNCTION	CURRENT ENGINE	GROWTH ENGINE	COMMENTS
Wf Control	X	X	
Stator Vane Control	X	X	
LPC Bleed Control	X	X	
HPC Bleed Control	X	X	
Reverse Fn Limiting	X	X	
Overspeed Protection	X	X	
Engine Heat Management Control	X	X	
Turbine Case Cooling Control	X	X	
Nacelle Cooling Control	X	X	
IDG AOCV Override	X		
TRC System	X	X	
TVBCA System	X	X	
Modulated TCA System	X	X	P&W Requirement
ARINC Receiver #1	X	X	
ARINC Receiver #2		X	Airframer Requirement
ARINC Transmitter #1	X	X	
ARINC Transmitter #2		X	Airframer Requirement
High-Speed ARINC 429 Transmitter		X	Airframer Requirement
Reverser Control	A/C	X	Airframer Requirement
Probe Heat Control	A/C	X	Airframer Requirement
Fuel On/Off Control	A/C	X	Airframer Requirement
Ignition Control	A/C	X	Airframer Requirement
Full Autostart	SCU	X	Airframer Requirement
MINIMUX Features	SCU	X	Airframer Requirement
Power convert (115 VAC)	N/A	X	Airframer Requirement
Mass Wf Transmission	EBU	X	Airframer Requirement
Oil Quantity Transmission	EBU	X	Airframer Requirement
NAC Temperature Transmission	EBU	X	Airframer Requirement
Pon Transmission	EBU	X	Airframer Requirement
TIDG Oil Transmission	EBU	X	Airframer Requirement
IDG Heat Management Control	EBU	X	Airframer Requirement
VSCF Heat Management Control	N/A	X	Airframer Requirement
Low NOX Burner System Control	N/A	X	Airframer Requirement
Oil ΔP Transmission	EBU	X	Airframer Requirement
Fuel ΔP Transmission	EBU	X	Airframer Requirement
Ram Air Turbine Deploy Signal	A/C	X	Airframer Requirement
HP Customer Bleed Valve Override	ECS	X	Airframer Requirement
Holdup Power	SCU	X	Airframer Requirement
PMA Health Monitor	N/A	X	Airframer Requirement



CONTROL REQUIREMENTS GROWTH

Doubling per decade



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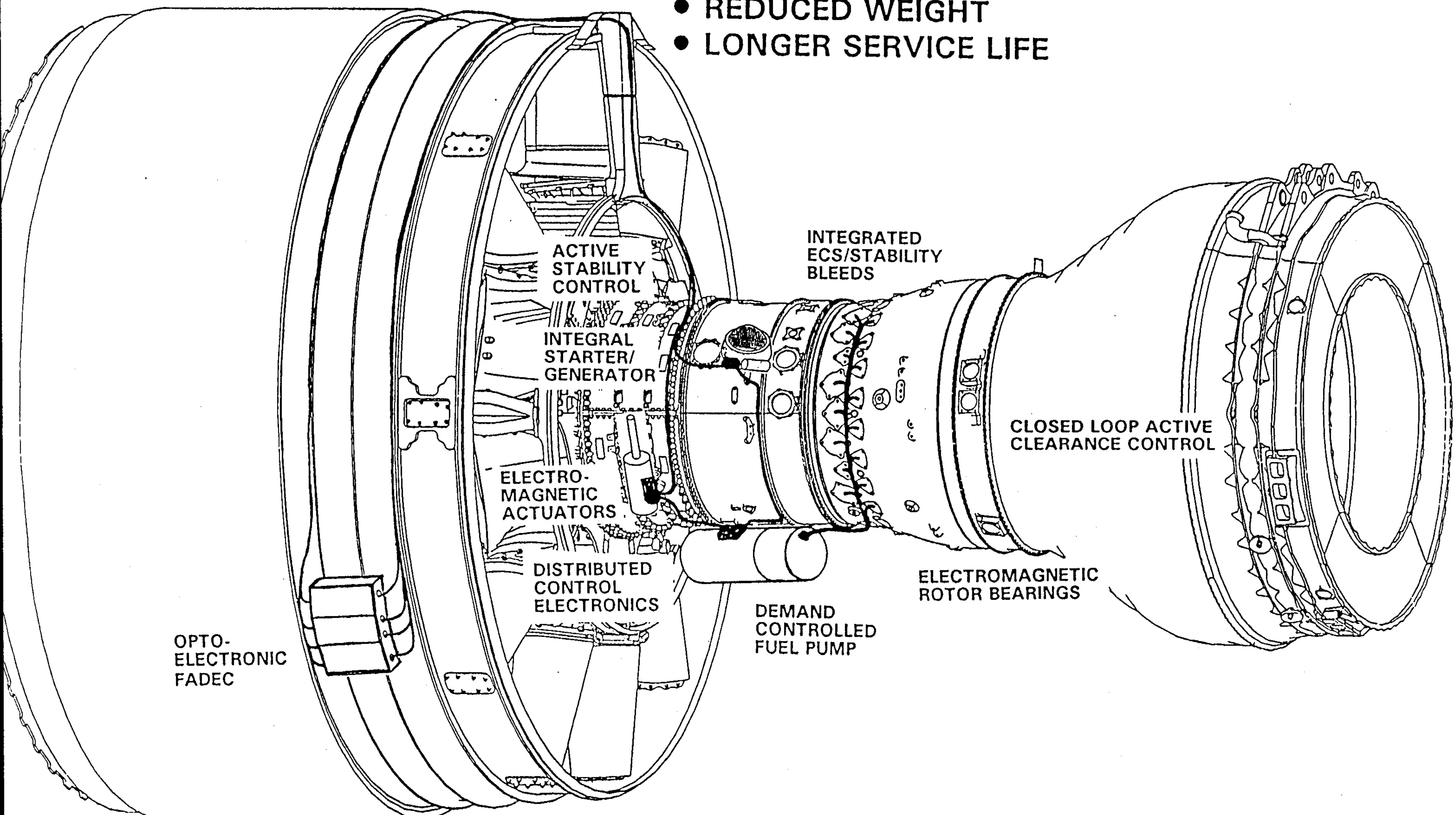
TO DATE, THE CONTROL STRATEGY HAS NOT CHANGED

- OPEN LOOP SCHEDULING
- CLOSED LOOP CONTROL

ADVANCED ENGINE CONTROLS

- GREATER ENGINE EFFICIENCY
- SIMPLIFIED EXTERNALS
- REDUCED WEIGHT
- LONGER SERVICE LIFE



ADVANCED ENGINE CONTROL POTENTIAL

ACTIVE CONTROL ENGINE

	BENEFIT
TOTAL SYSTEM BLEED MANAGEMENT	FUEL BURN
AIRCRAFT/ENGINE DRAG OPTIMIZATION	FUEL BURN
NACELLE BOUNDARY LAYER CONTROL	FUEL BURN
CLOSED LOOP CLEARANCE CONTROL	FUEL BURN
CLOSED LOOP TURBINE COOLING CONTROL	FUEL BURN
ACTIVE COMPRESSOR STABILITY CONTROL	FUEL BURN

ADVANCED ENGINE CONTROL POTENTIAL

MORE ELECTRIC ENGINE

	BENEFIT
INTEGRAL STARTER/GENERATOR	WEIGHT
DISTRIBUTED ELECTRONICS	WEIGHT
ELECTRICAL ACTUATION	WEIGHT
DEMAND CONTROL FUEL PUMP	WEIGHT
MAGNETIC BEARING	WEIGHT

GE Aircraft Engines
Advanced Engine Control Issues

RS Carpenter
3/21/94

Overview of Topics

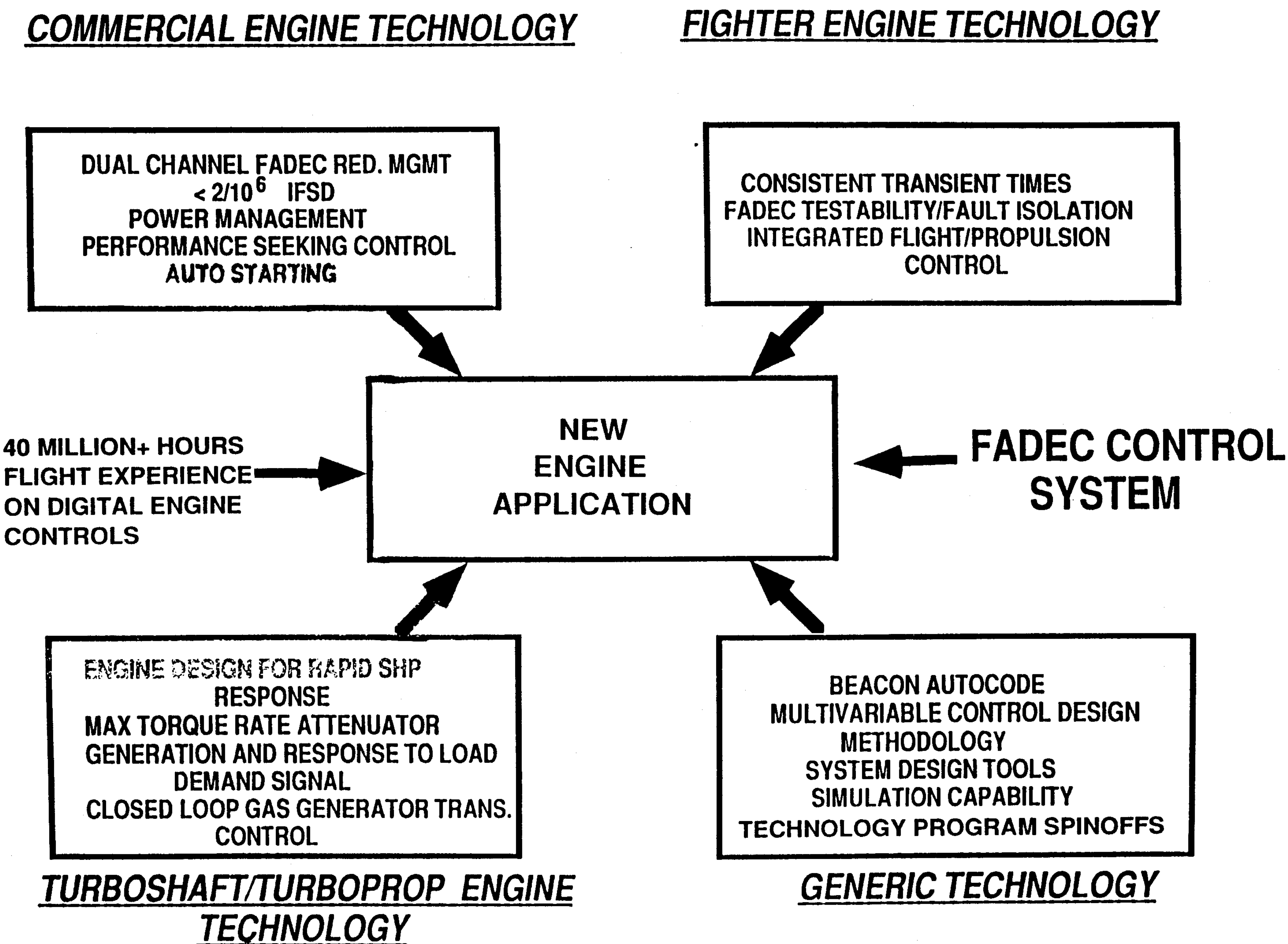
- Overall Technology Base
- Technology Trends in Controls Functionality
- Design Methods
- Unique Helicopter Issues
- Unique Land Vehicle Issues
- Conclusions

GEAE CONTROLS TECHNOLOGY BASE

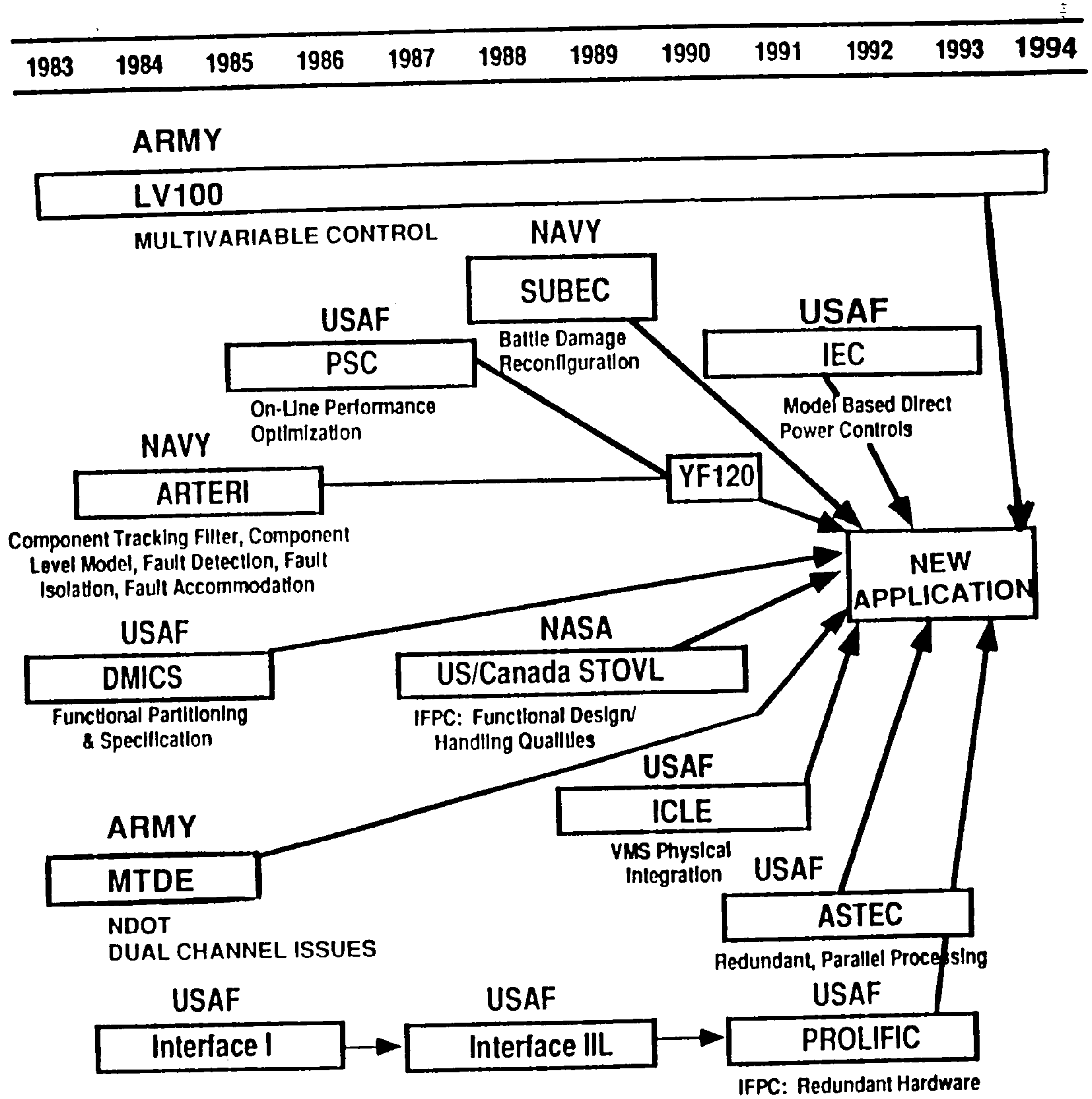
GEAE Controls Technology

- In last decade GEAE has made major commitment to introduce "State of the Art" controls on all new product engines
- GEAE Experience on all product lines directly relates to future new product control needs
- Emphasis on appropriate application of advanced control concepts, and I&RD/ demonstrator program spin offs to meet real world design requirements

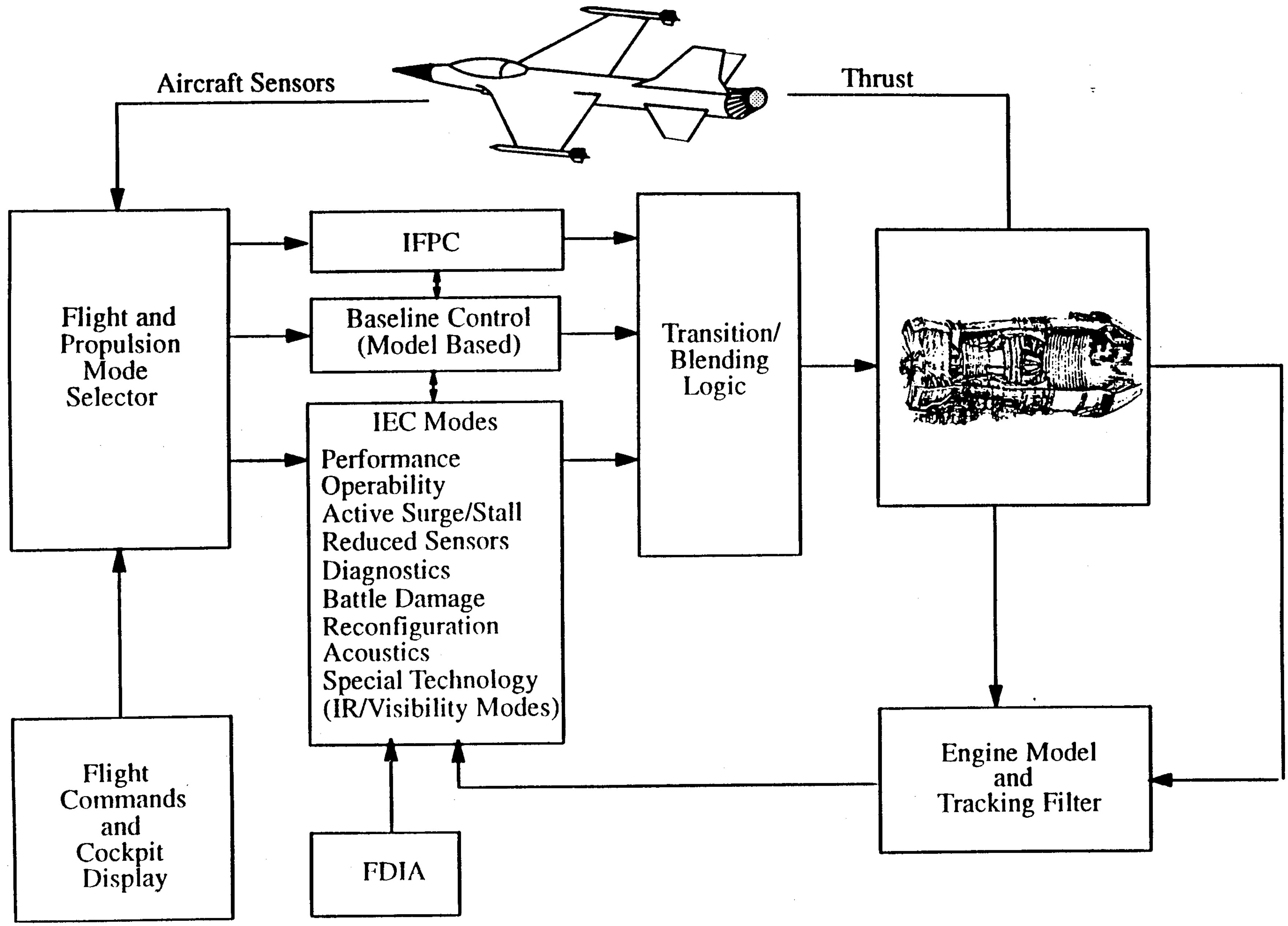
GEAE COMMITTED TO BE LEADER
IN ENGINE CONTROL SYSTEM TECHNOLOGY


COMMERCIAL ENGINE TECHNOLOGY
DUAL CHANNEL FADEC RED. MGMT
< 2/10^6 IFSD
POWER MANAGEMENT
PERFORMANCE SEEKING CONTROL
AUTO STARTING
FIGHTER ENGINE TECHNOLOGY
CONSISTENT TRANSIENT TIMES
FADEC TESTABILITY/FAULT ISOLATION
INTEGRATED FLIGHT/PROPULSION CONTROL
40 MILLION+ HOURS FLIGHT EXPERIENCE ON DIGITAL ENGINE CONTROLS
NEW ENGINE APPLICATION
FADEC CONTROL SYSTEM
ENGINE DESIGN FOR RAPID SHP RESPONSE
MAX TORQUE RATE ATTENUATOR
GENERATION AND RESPONSE TO LOAD DEMAND SIGNAL
CLOSED LOOP GAS GENERATOR TRANS. CONTROL
TURBOSHAFT/TURBOPROP ENGINE TECHNOLOGY
BEACON AUTOCODE
MULTIVARIABLE CONTROL DESIGN METHODOLOGY
SYSTEM DESIGN TOOLS
SIMULATION CAPABILITY
TECHNOLOGY PROGRAM SPINOFFS
GENERIC TECHNOLOGY

ADVANCED CONTROL LAW TECHNOLOGIES



TECHNOLOGIES WHICH CAN IMPACT FUTURE SYSTEMS BASED ON CUSTOMER REQUIREMENTS



Intelligent Engine Control (IEC) Concept.

GLOSSARY OF TERMS

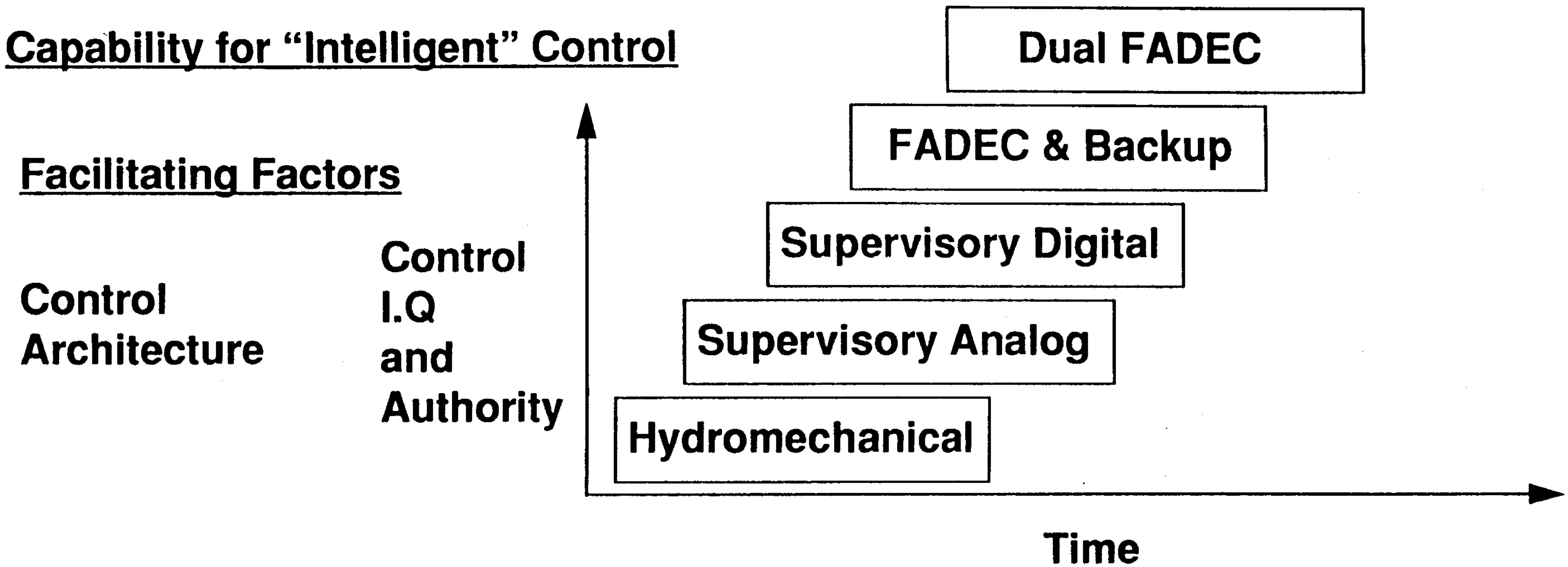
CONTRACTS

ARTERI	ANALYTICAL REDUNDANCY TECHNOLOGY FOR ENGINE RELIABILITY IMPROVEMENT
ASTEC	ADVANCED SIMULATION TECHNOLOGY FOR ENGINE CONTROL
DMICS	DESIGN METHODS FOR INTEGRATED CONTROL SYSTEMS
FOCSI	FIBER OPTIC CONTROL SYSTEM INTEGRATION
ICLE	INTEGRATED CONTROL LAW EVALUATION
IEC	INTELLIGENT ENGINE CONTROL
INTERFACE	INTEGRATED, RELIABLE, FAULT TOLERANT CONTROL FOR LARGE ENGINES
PROLIFIC	PROPULSION CRITICAL INTEGRATED CONTROL
PSC	PERFORMANCE SEEKING CONTROL
SUBEC	SURVIVABILITY BASED ENGINE CONTROL

OTHER TERMS

PMC	POWER MANAGEMENT CONTROL

Control Technology Trends



Facilitating Factors

Processor capability	16 Bit > 32 Bit > Fast 32 Bit floating point with CACHE
Memory Affordability	>16 X growth in digital control memory capacity
Design Methodology	Great advances in multivariable design methods, simulation capability, computer horsepower, and smorgasboard of "intelligent" concepts
System & S/W process	Integrated control law design/analysis with pictures to code system allows affordable useage of complex control laws

Great advances in ability to develop/incorporate intelligent engine control features

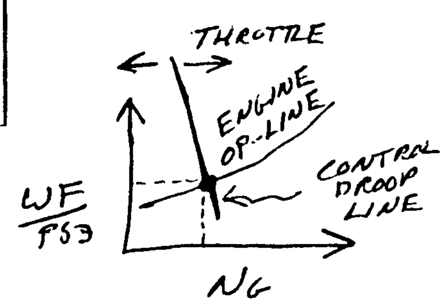
EVOLUTION OF INTELLIGENCE

- NATURAL EVOLUTION OF CONTROL FUNCTIONALITY TO RELY ON INTELLIGENT CONTROL TECHNIQUES TO HELP MEET EVER TIGHTER PERFORMANCE REQUIREMENTS

GOVERNOR LOOP DESIGN

INTELLIGENCE

	BENEFITS	COMMENT
HIGH PERFORMANCE DIGITAL MIMO W/GAIN SCHEDULING	CONSISTENT HIGH PERFORMANCE OVER OPERATING REGIME, SS SFC	CURRENT APPROACH ON DEV/DEMO PROGRAMS
SOPHISTICATED GAIN SCHEDULING	CONSISTENT HIGH PERFORMANCE OVER OPERATING REGIME	CURRENT APPROACH WHEN MIMO N/A
DIGITAL ELECTRONIC ISOCHRONOUS	IMPROVED ACCURACY/ PERFORMANCE	ADDED FLEXIBILITY FOR GAIN/ DYNAMICS TAILORING
ANALOG ELECTRONIC ISOCHRONOUS	IMPROVED ACCURACY/ PERFORMANCE	
HYDROMECHANICAL DROOP (PROPORTIONAL)	NO EMI OR ELECTRICAL POWER LOSS ISSUES	



TIME

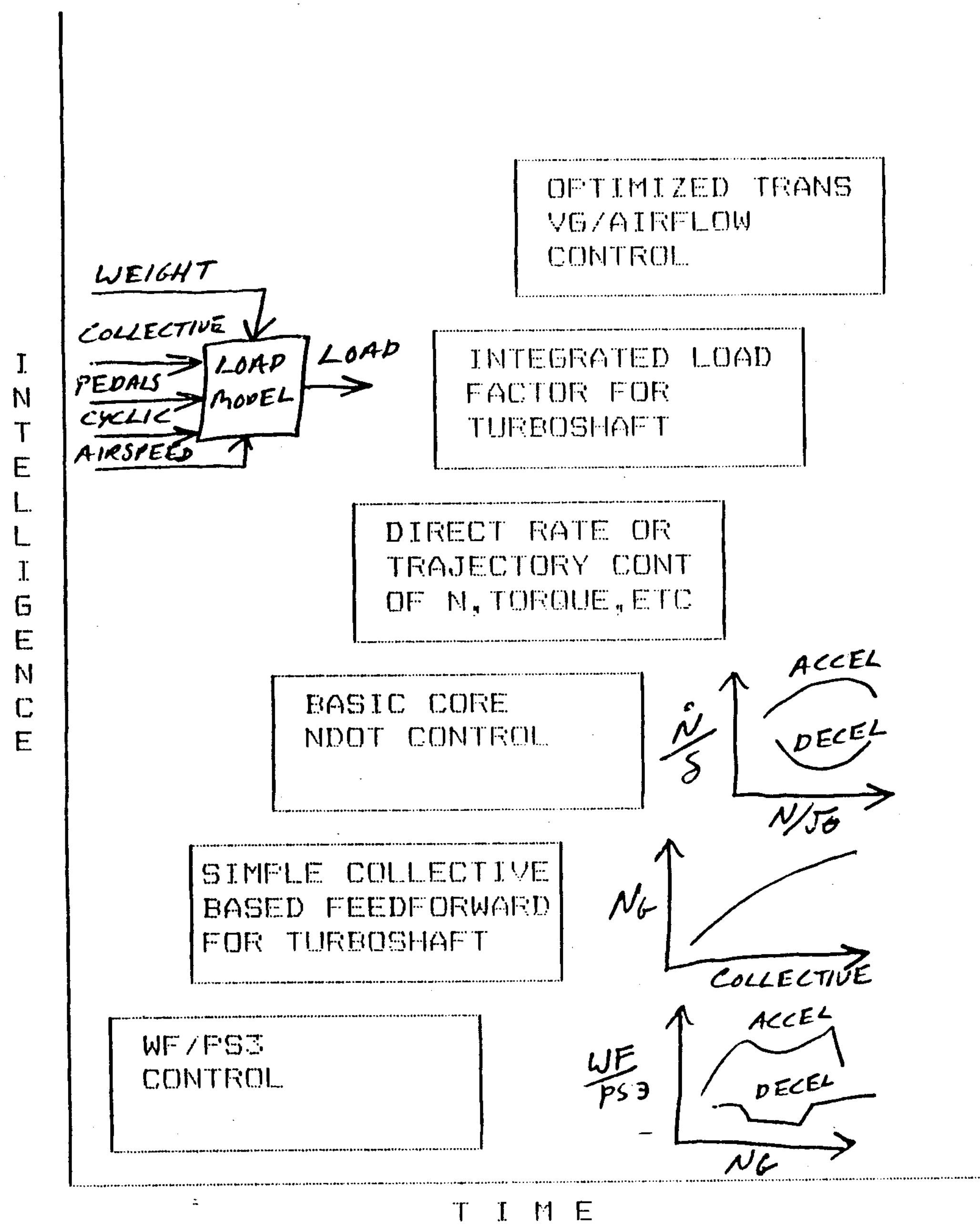
CONTROL SCHEDULING

INTELLIGENCE / TIME	BENEFITS	COMMENT
PERFORMANCE SEEKING CONTROL	OPTIMIZED SYSTEM SFC, FN, NOISE, EMISSIONS	PART OF IFPC STUDY
MODEL-BASE SCHEDULING	HIGHER PERFORMANCE, W/MARGIN, W/O EXTRA SENSORS	ON GE CERTIFIED ENGINES
COMPOSITE MODES	EXPLOIT ENGINE PERF WHILE HOLDING STALL/SFC MARGIN	CONTROL CYCLE PARAM BEYOND JUST SENSOR SET
POWER MANAGEMENT	SET REQUIRED POWER FOR MISSION PHASES AUTOMATICALLY	GE COMMERCIAL PRODUCTION
MULTI-VARIATE	IMPROVED FLEXIBILITY TO TAILOR SCHEDULING	
SIMPLE MONO-VARIATE	ALLOWED SCHEDULING TO NON-CONSTANT LIMITS	

INTELLIGENCE

T I M E

TRANSIENT CONTROL STRATEGY



BENEFITS	COMMENT
MORE RAPID POWER RESPONSE/ DISTURBANCE REJECTION	
SMARTER FF REDUCES "UNCOMPENSATED" MANEUVERS	IN PRODUCTION.
OPTIMIZED PERFORMANCE, LIMIT PROTECT, HANDLING QUALITIES	COMBINED W/ ALL BELOW FOR MIXED MODE TRANS CONTROL THAT FULLY EXPLOITS ENGINE CYCLE CAPABILITY
STALL MARGIN, LIFE, TRANSIENT CONSISTENCY	
EFFECTIVE LOAD ANTICIPATION FOR MOST COLLECTIVE TYPE MANEUVERS	
GOOD BASIC STALL/BLOWOUT PROTECTION AND TRANSIENT HANDLING	

ENGINE OPERABILITY CONTROL

	BENEFITS	COMMENT
ACTIVE COMPRESSOR STABILIZATION	STALL LINE, SFC, DISTORTION TOLERANCE	IN RESEARCH PHASE
ACTIVE STALL RECOVERY	ENHANCED STALL RECOVERY	UNIQUE DETECTION AND CONTROL SCHEDULING
INTELLIGENT INLET BUZZ PREVENTION	FASTER SUPERSONIC DECELS	SUPERSONIC APPLICATIONS ONLY!!!
HIGH-BANDWIDTH PRESSURE RATIO CONTROL	TIGHT OP-LINE CONTROL FOR REDUCED STALL MARGIN LOSS	ENGINES WITH VARIABLE EXHAUST NOZZLE
UNIQUE TRANSIENT VG SCHEDULING	BUYS TRANSIENT STALL MARGIN, ALLOWS USING FULL CYCLE ACCEL/DECEL CAPABILITY	INDEPENDENT BLEED ON AXI-CENTRIF MACHINES
GE MIXED MODE TRANSIENT CONTROL, W/NDOT	SAME AS ABOVE	BLEND OF WF/PS3, NDOT, TRAJECTORY AS APPROPRIATE
WF/PS3 ACCEL/ DECEL AND SIMPLE VG SCHEDULING	BASIC OPERABILITY, STALL RECOVERY, BLOWOUT PROTECTION	

INTELLIGENCE

TIME

STARTING

	BENEFITS	COMMENT
ADAPTIVE START FLOW SCHEDULING	HANDLES BROAD RANGE OF FUEL TYPES, NATURAL GAS FOR M&I	
FULLY AUTOMATIC STARTING	FULLY HANDS OFF, EYES OUT OF COCKPIT	COMBINING STRATEGIES BELOW
HUNG START PREVENTION	SUCCESSFUL START FOR WEAK STARTER, LEAN FUEL SCHEDULE	
NDOT STARTING AND VARIABLE MIN FLOW	COOL, CONSISTENT, RELIABLE STARTS OVER ENHANCED START ENVELOPE	
HOT START PREVENTION	HOT PARTS PROTECTION	
AUTO RESTART/ RELIGHT	RAPID RECOVERY FROM FLAMEOUT	
FIXED MIN FLOW PLUS WF/PS3 SCHEDULE	GOOD BASIC AUTOMATIC START FUEL SCHEDULING	

INTELLIGENCE

TIME

FAULT DETECTION AND RESPONSE

INTELLIGENCE	BENEFITS	COMMENT
FUZZY LOGIC INPUT SIGNAL SELECTION	INTELLIGENT IN-RANGE FAULT ACCOMMADATION	PHASING IN DEVELOPMENT PROGRAMS
ANALYTIC REDUNDANCY	ADDED FAIL-OP CAPABILITY IF ALL SOURCES OF A SIGNAL FAILED	USED SELECTIVELY ON CURRENT PROGRAMS
PHYSICAL REDUNDANCY	ADDED FAIL-OP CAPABILITY	CURRENT FADECS USE ALL BELOW
SOPHISTICATED SYSTEM LEVEL ERROR CHECKING	INCREASED FAULT COVERAGE	OUTPUT WRAPS, SERVO TRACKING, CYCLE RELATIONSHIPS
BASIC BIT: CPU TESTS, RANGE TESTS	GOOD COVERAGE OF "COMPUTER" PART OF CONTROL, AND INPUTS	
SIMPLE FAILSAFE RESPONSE	MAINTAINS ENGINE IN A SAFE CONDITION	PRIMARILY FOR HYDRO AND ANALOG CONTROLS

TIME

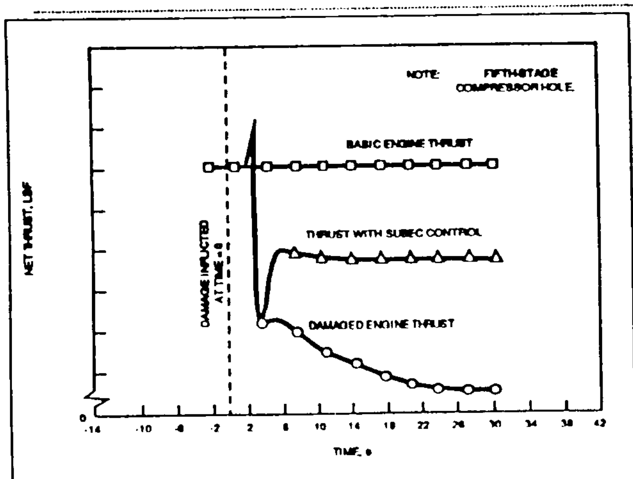
MAINTAINABILITY/FAULT DIAGNOSTICS

	BENEFITS	COMMENT
SOPHISTICATED ON-BOARD FAULT ISOLATION	ISOLATES TO FAULTY COMPONENT (WRA) OR SRA	PROCESSES RAW BIT INFO, INITS ADDED TESTS AND APPLIES "KNOWLEDGE" BASED TYPE REASONING
MORE EXTENSIVE RECORD/REPORT OF FAULT EVENTS	RECORDS WHAT WAS HAPPENING IN VICINITY OF FAULT EVENTS	
DIGITAL COMMUNICATION OF FAULT INFO	INTEGRATION W/ COCKPIT DISPLAY, GROUND BASED DIAG SYSTEM	ALL GE FADECS
EXTERNAL VISUAL FAULT INDICATION	COMMUNICATE RESULTS OF BIT FOR TROUBLESHOOTING	ELECTRO-MECHANICAL BALLS
DIAGNOSTIC TEST CONNECTOR	MEASURE CONTROL PARAMS W/O DISSASSEMBLY	ANALOG AND DIGITAL CONTROLS

INTELLIGENCE

TIME

SURVIVABILITY



Simulation of an F404 engine upon receiving combat damage to the high-pressure compressor case shows capabilities of advanced controls in maximizing performance. Here, SuBEC control algorithms restore most of the thrust loss that would result with usual control laws.

	BENEFITS	COMMENT
SURVIVABILITY BASED ENGINE CONTROL	MAINTAIN SAFE ENGINE THRUST FOR ENGINE DAMAGE	DAMAGE DETECTION & ADAPTIVE/ MODEL BASED CONTROL
CONTROL FAULT TOLERANCE AND REDUNDANCY	FAIL OPERATIONAL WITH CONTROL FAILURES	
FUEL SYSTEM DESIGN	REDUCED FIRE HAZARD	MINIMIZE/ CONTROL DAMAGE CAUSED LEAKS
CONTROL COMPONENT PLACEMENT	REDUCED CONTROL COMPONENT VULNERABILITY	

INTELLIGENCE

TIME

EMISSIONS

GE HEAVILY COMMITTED TO TECHNOLOGIES TO MEET EVER MORE STRINGENT EMISSIONS REQUIREMENTS, CONTROL TECHNOLOGY IS KEY

INTELLIGENCE / TIME	BENEFITS	COMMENT
MULTI-ANNULAR COMBUSTOR, ACTIVE FLAME TEMP CONTRL	CONTROLLED NO_x AND CO W/O STEAM	APPLICABLE TO M&I & AIRCRAFT
STEAM INJECTION	REDUCED NITREOUS OXIDE EMISSIONS	APPLICABLE TO M&I ONLY
AFTERBURNER VAPOR PUFF PREVENTION	REDUCED INCIDENCE OF VISIBLE VAPOR PUFF DURING A/B START/SHUTDOWN	ONLY W/AB
FUEL RECYCLE UNIT	ADDRESSES LIQUID FUEL DISCHARGE DURING SHUTDOWN	
SMOKELESS COMBUSTOR	BURNS CLEAN W/O VISIBLE SMOKE (CONTROL ENGINEERS DREAM)	NO SPECIAL CONTROL STRATEGIES!

MODEL BASED CONTROL

- CRITICAL PART OF TODAY'S DESIGNS... SOME EXAMPLES:

MODELS USED TO ACHIEVE SENSOR TIME CONSTANT CORRECTION, AFTERBURNER FUEL SCHEDULING, AND LOW EMISSIONS BY CONTROLLING PREDICTED FLAME TEMPERATURE

INPUT SENSOR AND SERVO LOOP FAILURE DETECTION, SENSOR VOTING, AND SENSOR SUBSTITUTION

IMPLIED T41 AND STALL MARGIN BUILT INTO SMART REFERENCE SCHEDULES

SIMPLE MAP MODELS OR MORE COMPLEX COMPONENT LEVEL EMBEDDED MODELS USED DEPENDING ON ACCURACY REQUIREMENTS

- INCREASING ROLE IN THE FUTURE:

INCREASED EMPHASIS ON DESIGN FOR SURVIVABILTY (DETECTION AND RECONFIGURATION FOR BATTLE DAMAGE)

INTEGRAL PART OF PERFORMANCE SEEKING CONTROL

DIRECT CONTROL TO MODEL BASED PARAMETERS

GREATER USE OF ANALYTIC REDUNDANCY

TREND MONITORING AND DIAGNOSTICS

INCREASED VEHICLE SYSTEM INTEGRATION/OPTIMIZATION

CONCLUSIONS ON EVOLUTION

- SUBSTANTIAL EVOLUTION IN CONTROL STRATEGIES HAS BEEN OCCURRING, WITH ASPECTS OF INTELLIGENT CONTROL PHASING INTO PRODUCT AND NEAR TERM DEVELOPMENT PROGRAMS

- GENERALLY DRIVEN BY SPECIFIC PROGRAM NEEDS AS CUSTOMERS CONTINUE TO ASK FOR MORE FROM THEIR ENGINES

REGARDING TOOLS

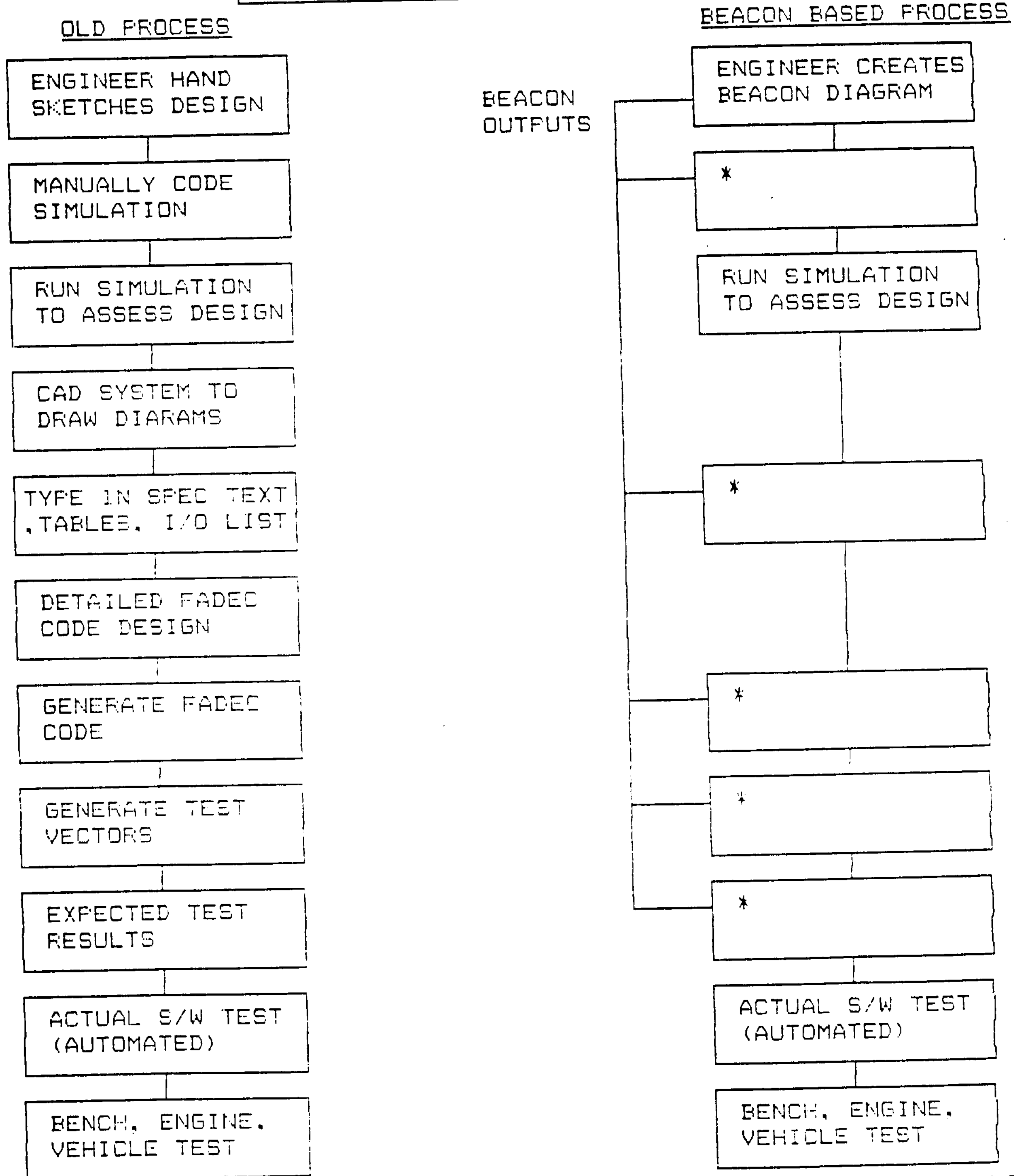
- COMPREHENSIVE TOOLSETS FOR DESIGN, ANALYSIS, AND SIMULATION HELP MAKE INTELLIGENT CONTROL MANAGEABLE

GE DRAWS ON A VARIETY OF ADVANCED SIMULATION METHODS FOR INTEGRATED TOTAL CONTROL/ENGINE SYSTEM DEVELOPMENT

	BENEFITS	COMMENT
FULL CONTROL SYSTEM H/W IN THE LOOP FACILITY	COMPREHENSIVE CONTROL SYSTEM TEST PRIOR TO ENGINE	TOTAL SYSTEM SIMULATION CAPABILITY
HIGH FREQUENCY MODELLING: FUEL SYSTEM, ENGINE	ALLOWS GREATEST PERFORMANCE IN TODAY'S HIGHLY COUPLED SYSTEMS	NON-LINEAR, COMPRESSIBLE EFFECTS
AUTO-GENERATED COMPLETE CONTROL MODEL	RAPID AVAIL-ABILITY OF ERROR FREE COMPLETE CONTROL MODEL	BEACON CODE INTEGRATED TO CYCLE WORK STATION SYSTEM (CWS)
CLOSED LOOP FADEC TEST WITH REAL TIME MODEL	VERIFICATION OF CONTROL LAW IMPLEMENTATION PRIOR TO ENGINE	
INTEGRATED ENGINE/VEHICLE SYSTEM MODEL	VEHICLE/ENINE INTERACTIONS, AND PREDICTION OF HANDLING QUALITIES	VITAL FOR HELICOPTER, TILTROTOR, VSTOL, AND LAND VEHICLES
COMPONENT LEVEL ENGINE MODEL	MOST ACCURATE FOR OPTIMIZATION/ PREDICTIONS	TYPICALLY GE'S CWS, CYCLE WORK-STATION SYS
PIECE-WISE LINEAR ENGINE MODEL	COMPACT, DYNAMICALLY ACCURATE SIMULATIONS	

GE'S BEACON SYSTEM:
PROVIDES INTEGRATED CONTROL LAW DESIGN, IMPLEMENTATION, AND TEST,
WITH DRAMATIC TOTAL PROCESS COST AND CYCLE TIME REDUCTION,
QUALITY ENHANCEMENT, AND SIGNIFICANT REDUCTION IN MANUAL STEPS

SIMPLIFIED PROCESS DIAGRAM



* = AUTOMATED COMPUTER UTILITIES AND BEACON OUTPUT USED TO ACCOMPLISH THIS TASK

NOTE: FOR CLARITY, DESIGN ITERATION IS NOT SHOWN, NOR ARE ALL DETAILED PROCESS STEPS

LINEAR ISSUES:

NEED TOOLS THAT ALLOW CONSTRAINED STRUCTURE CONTROL LAW SYNTHESIS.

Currently, most multivariable designs are done using Model Matching (KQ) because company developed software allow controller structure constraints to be entered before optimization. Other toolboxes such as H Infinity do not provide this capability.

Linear analysis tools such as Structured Singular Values are well developed and meet our needs better than the linear design tools.

NONLINEAR ISSUES:

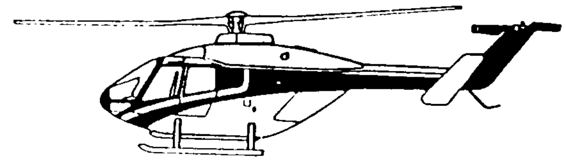
NEED A MORE ANALYTICAL APPROACH TO NONLINEAR DESIGN

Currently depend solely on transient simulations to evaluate nonlinear stability.

Multivariable/Multimode Selection Logic (Limit Protection, Stability).

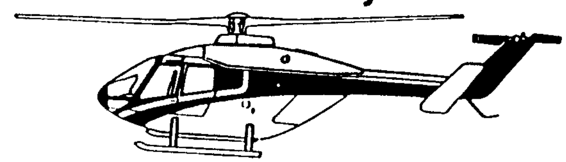
How to guarantee that approaching a linear governor from a new direction will not cause limit cycling due to nonlinearities such as gain kickers.

Unique Helicopter Issues



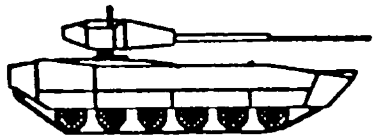
- **Background**
  - Extensive GE Experience on Helicopter applications through T58/T64/T700 product line
  - Numerous military/commercial applications, including single/dual/triple engines
- **Unique Issues**
  - Helicopter applications inherently a challenging load disturbance rejection problem
  - Increasingly aggressive manuvers, low rotor inertia, low transmission torque limit, and eyes out of cockpit flying result in increased performance demands on engine/ control and drive control law complexity
  - Multiple engines coupled through rotor system drivetrain drives need for load share function & good OEI strategies
  - New VSTOL designs require mode transition
  - Difficult to specify aircraft handling qualities drivers on engine system perfromance

- **Past Approach**
  - Highly refined supervisory electrical control architecture cost effectively meets today's performnace demands
  - NP and load share loops spectrally seperated
  - Collective based load anticipation signal
  - Np governor adapts gains based on rotor coupled/decoupled, and Np error/rate conditions
  - Torque trajectory shaping employed to control rate of torque rise at power



- **Relevant Technologies For Future Application**
  - FADEC for stringent performance reauirements, cockpit integration, and fail operational capability
  - Higher bandwidth Np governing (with combustive damping) for load rejection in light of continued trend of aggressive maneuvers and low rotor inertias
  - True Np/Q mimo design with optimized gain scheduling for tight loadshare and torque trajectory performance
  - Intelligent load factor allowing compensation for pedal and cyclic inputs
  - Multi-mode transient control for fastest/consistent accels
  - VG overclosure during autorotation to enhance axi-centrif machine power vs. ng characteristic
  - Integrated vehicle management allowing interchange of limits and other info for optimal vehicle system control
  - Integrated vehicle/engine PSC for optimizing total system (E.G. tailor Nr for best cruise fuel burn, noise,maneuver load capability, etc.)

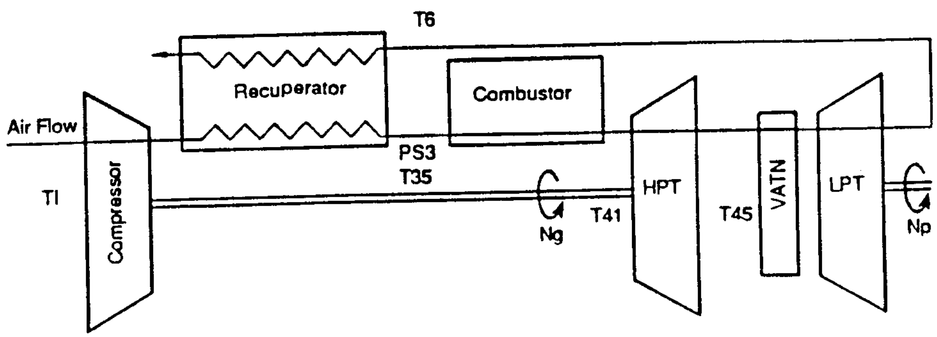
GE will continue to draw on Experience across product lines and appropriate advanced technologies to provide cost effective helicopter controls that meet operational needs



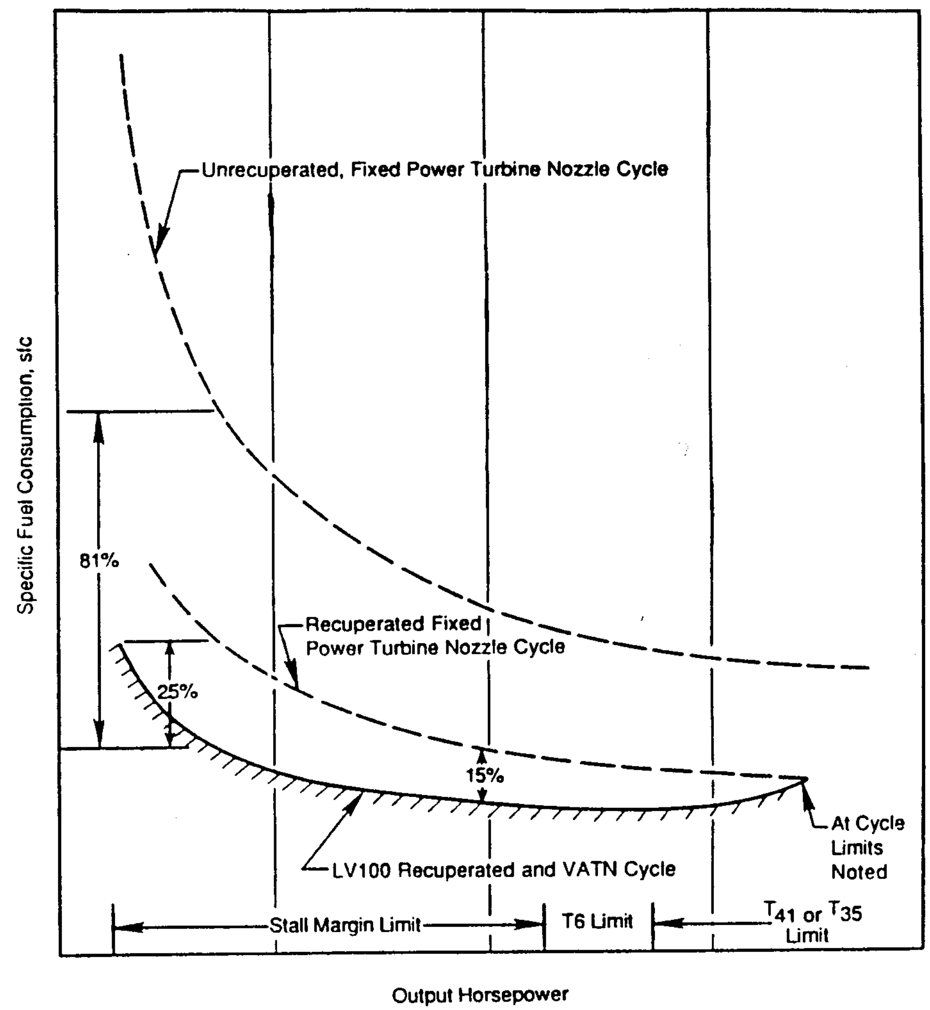
Unique Land Vehicle Issues

- **Background**
  - LV100 Demonstrator program ongoing since early 80's sponsored by US ARMY Tank-Automotive Command
  - Technology Demonstration of Electric Actuation/Fuel pump and multivariable control
- **Unique Issues**
  - Minimizing idle fuel flow and attaining great SFC are key
  - Engine cycle utilizes recuperator to help achieve above
  - Variable area turbine nozzle (VATN) allows greatest realization of recuperator benefits
  - Multivariable control of core speed and turbine discharge temperature allow near minimum SFC over power range
  - Normal control operation is analogous to turboprop control, throttle controls engine power, "load" controls power turbine speed

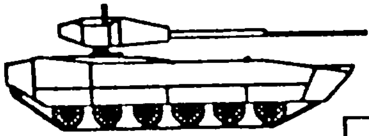
RECUPERATED ENGINE CYCLE AND BENEFITS



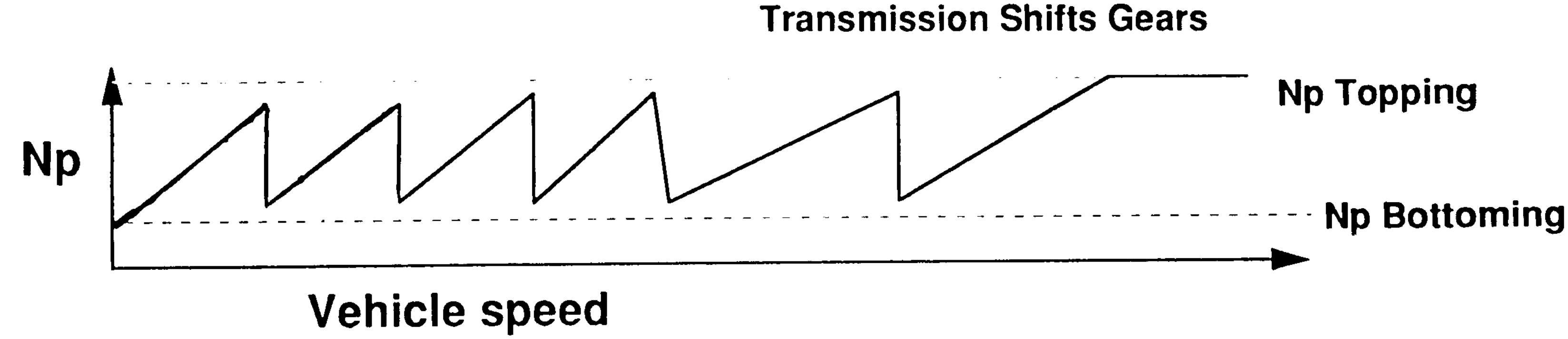
Simple Cross Section of a Turboshaft Engine with Heat Exchanger.



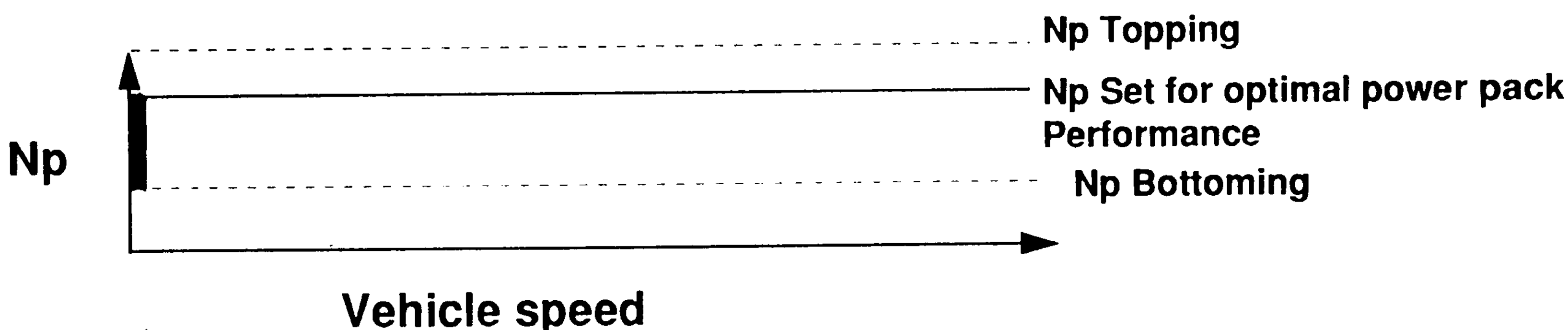
Comparison of Engine Cycles; Benefit of Recuperator and VATN. *The sfc of a recuperated turboshaft is significantly lower than that of a standard turboshaft.*

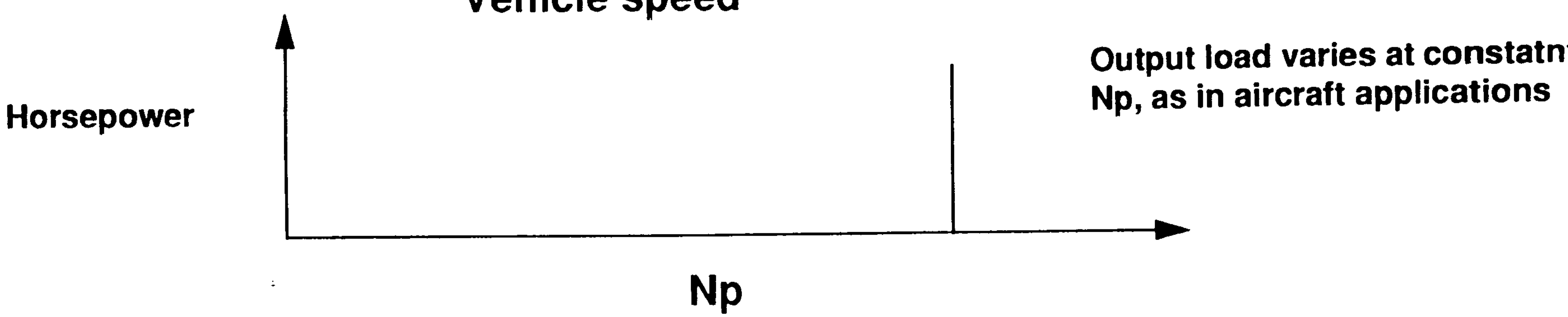


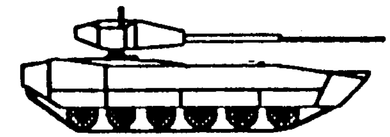
Hydro-Kinetic Transmission



Electric Drive Train







- **Unique issues (cont'd)**
  - Low cost another key requirement, drives reduced sensor set
  - Adaptive starting and decel control for range of fuel types and recuperator heat soak conditions
  - Multi-mode transient control with varying recuperator heat input back into cycle
  - Load loss/management impact on overspeed potential with recuperator
  - Engine dynamics with recuperator
  - Transient VATN control (opening VATN quickly accels gas generator, but can cause power dip)
  - Control of auxiliary functions (e.g. blowers)
  - Reflected vehicle inertias impact on Np governor design
- **Potential Future Relevant Technologies**
  - PSC for optimal engine performance over life with reduced sensor set

Conclusions

- Advances in methodology and computer horsepower have placed plethora of intelligent control possibilities at disposal of control system developers
- Digital control processor power can be available as needed, but costs $’s and weight... advanced features generally need to buy their way onto engine through life cycle cost savings or addressing stringent performance requirements
- Increased dependency on model based approaches for enhanced performance, better SFC, reduced emissions, and enhanced fault tolerance
- Fuzzy logic concepts providing benefits in area of soft fault tolerance
- Performance seeking control holds promise for turbofan/turboprop SFC/thrust benefits, and helicopter cruise fuel burn/noise reduction
- Integrated system design and control/engine/vehicle simulation tools help make complexity manageable
- Additional work needed on multivariable design techniques to better address real world constraints

“Intelligent” Control Concepts will continue to play a vital role in meeting ever more demanding performance requirements

THE PROMISE OF ACTIVE CONTROL FOR HELICOPTER AND TANK ENGINES

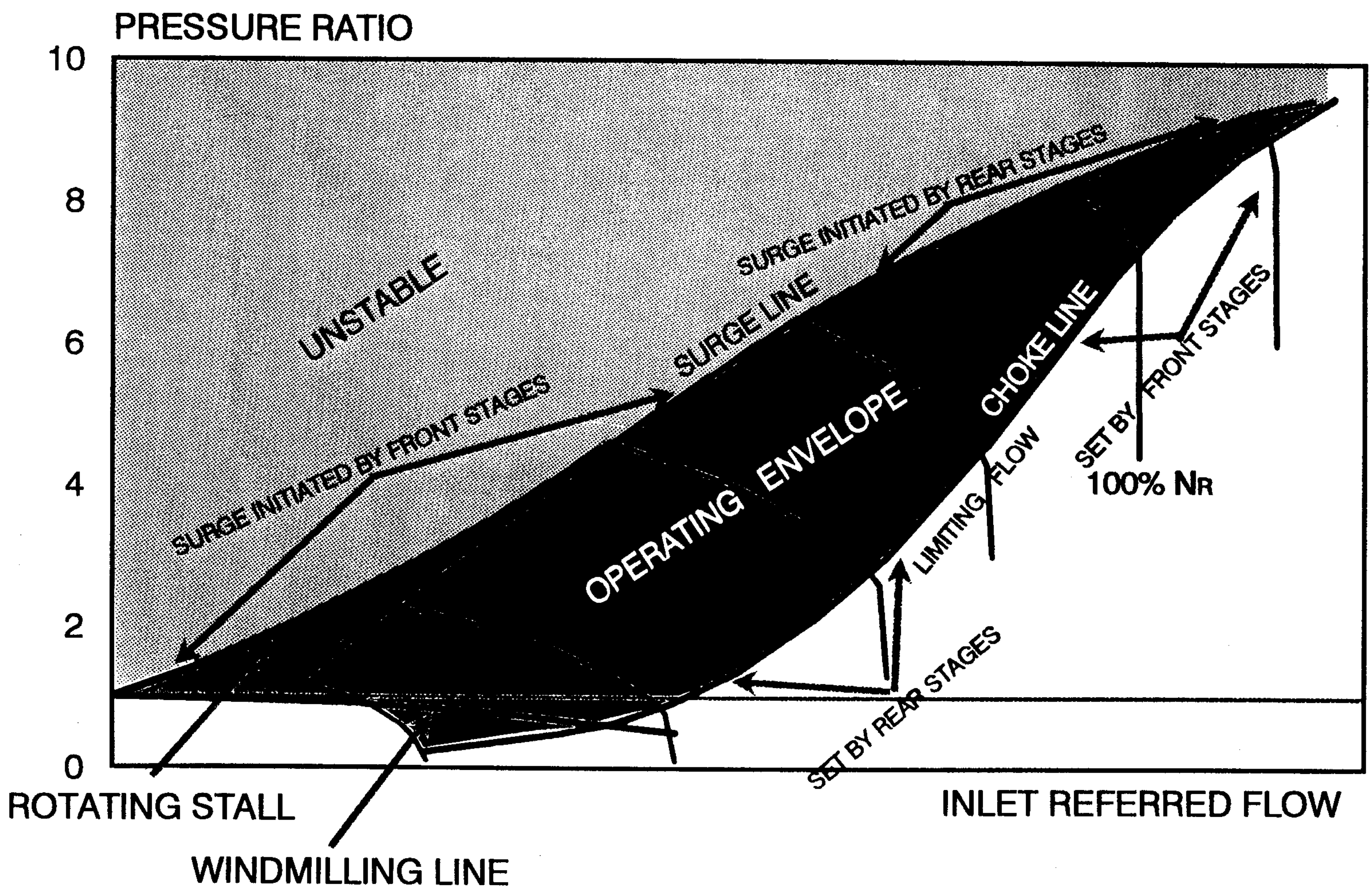
ARUN K. SEHRA
MANAGER, COMPRESSOR AERODYNAMICS
TEXTRON LYCOMING, STRATFORD, CT 06468

WORKSHOP ON INTELLIGENT TURBINE ENGINES FOR ARMY APPLICATION
MARCH 21-22, 1994
M.I.T., CAMBRIDGE, MASS

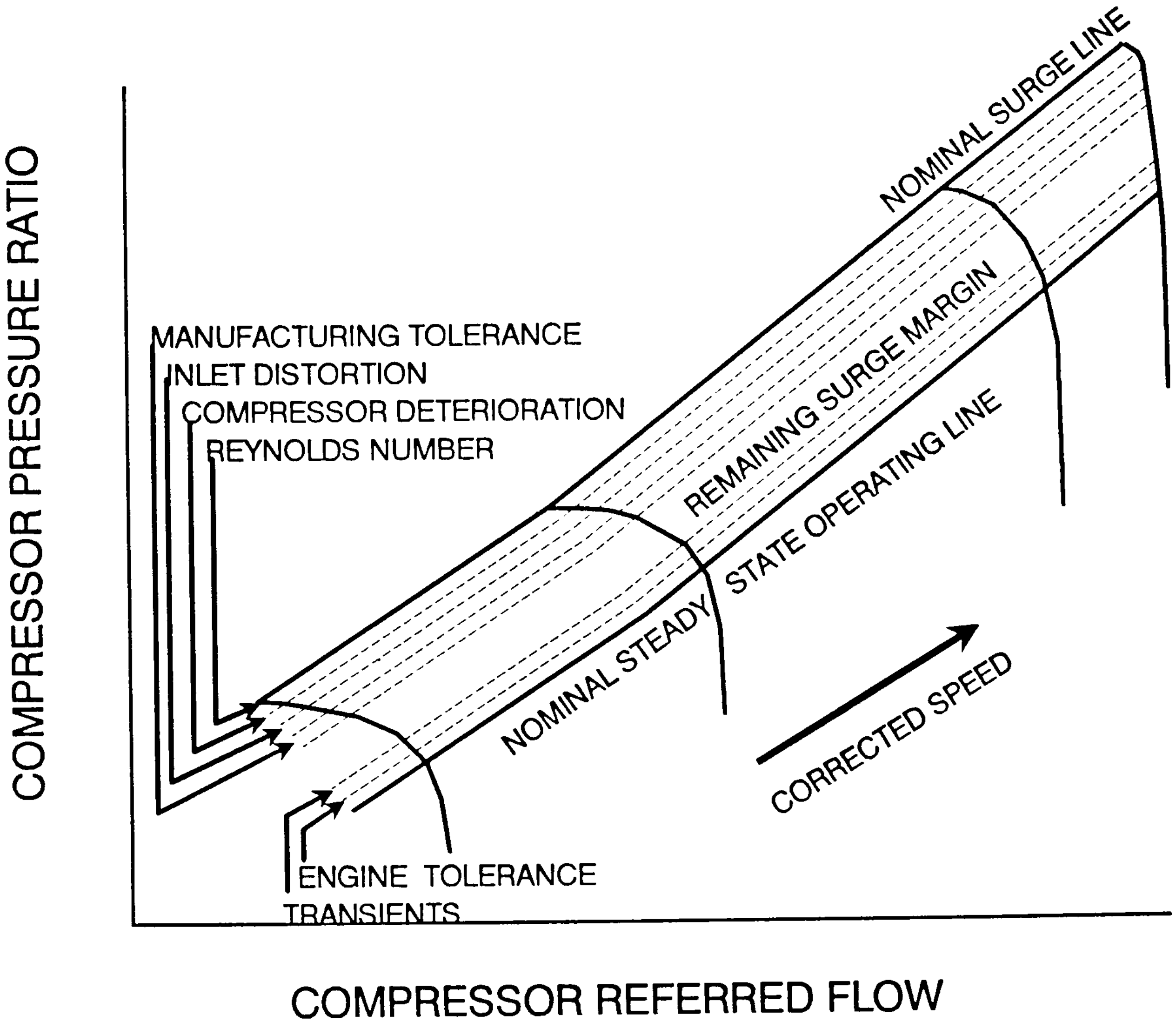
AGENDA

- COMPRESSOR/ENGINE OPERABILITY
- OPERABILITY ENHANCEMENT
- ACTIVE STABILIZATION - PAYOFFS & APPLICATION
  - HELICOPTER ENGINE APPLICATION
  - TANK ENGINE APPLICATION
- ISSUES & CONCERNS
- CONCLUDING MESSAGE

COMPRESSOR OPERATING ENVELOPE



STABILITY AUDIT



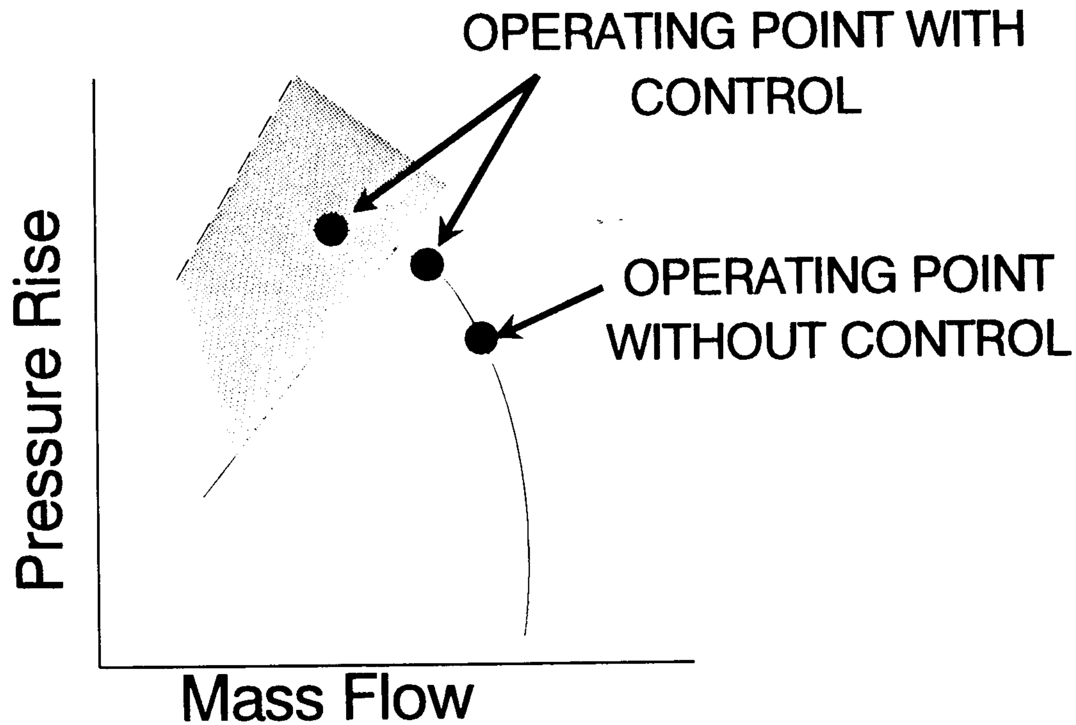
SURGE MARGIN ENHANCEMENTS

SM ENHANCEMENT DEVICE	ENGINE	IMPACT
ADD MORE STAGE(S)		INC. SIZE, WT., & COMPLEXITY, REDUCED RELIABILITY
INCRESED SPEED		INC. WT., REDUCED EFF.
VARIABLE GEOMETRY *	AGT1500 & T53	INC. WT. & COMPLEXITY, REDUCED EFF.
BLEEDS *	ALL ENGINES	INC. WT. & COMPLEXITY, REDUCED EFF. & POWER
CASING TREATMENT *	[redacted]	REDUCED EFF.
DUAL SPOOLING *	AGT1500	INC. WT., SIZE, & COMPLEXITY
OTHER DEVICES	LTS101	

* Primarily for part speed surge margin

ACTIVE STABILIZATION

PAYOFFS



- IMPROVED OPERABILITY RANGE
- IMPROVED SPECIFIC FUEL CONSUMPTION
  - HIGHER CYCLE PRESSURE RATIO
  - HIGHER EFFICIENCY

ACTIVE STABILIZATION

APPLICATION TO HELICOPTER & VEHICULAR ENGINES

Results of an In-house study corressponding to a 10% reduction of surge margin requirement for the following Lycoming engines

- T55
- COMMON CORE (T55 DERIVATIVE)
- LTS101
- AGT1500

ACTIVE SURGE CONTROL PAYOFFS

T55

DESIGN PT. SFC REDUCTION: 4.0%

IDLE FUEL CONSUMPTION REDUCTION: 5.6%

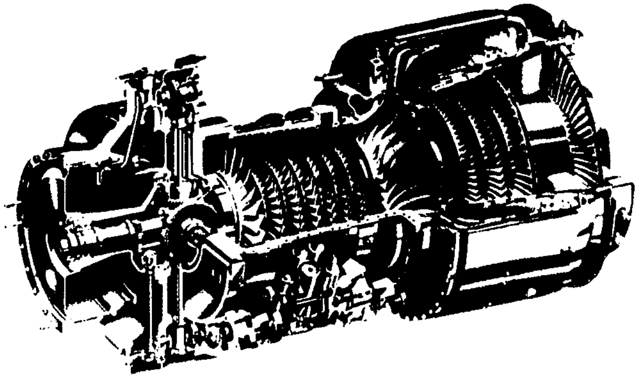
OPERABILITY FROM 25 K TO 39 K FEET ALTITUDE

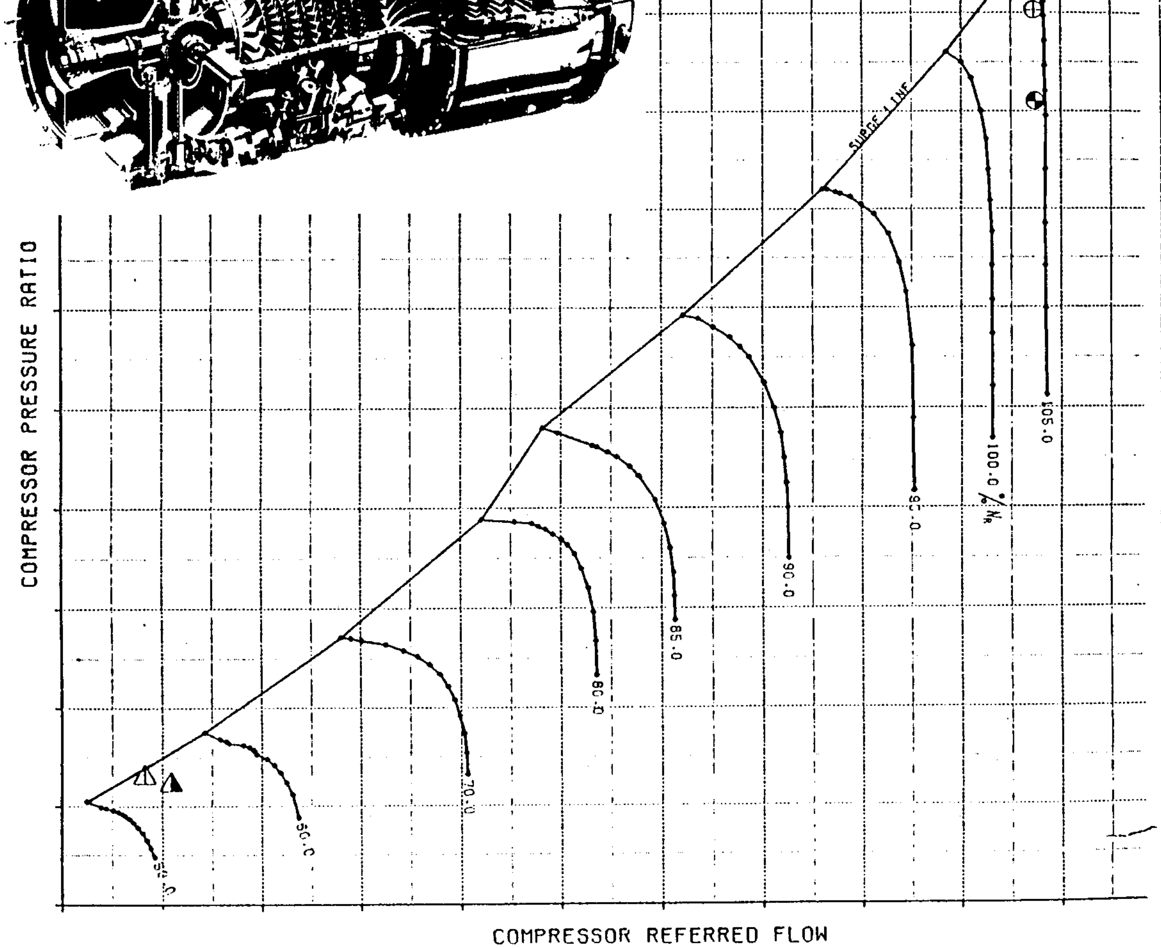
STEADY STATE INLET PRESSURE DISTORTION
CAPABILITY   DI FROM 0.03 TO 0.23

where $DI = \dfrac{P_{T\,MEAN} - P_{T\,LOW\,MEAN}}{P_{T\,MEAN}} \times K_P$

K_P = Factor to acount for shape, extent, & radial content
$= \sqrt{MER}$

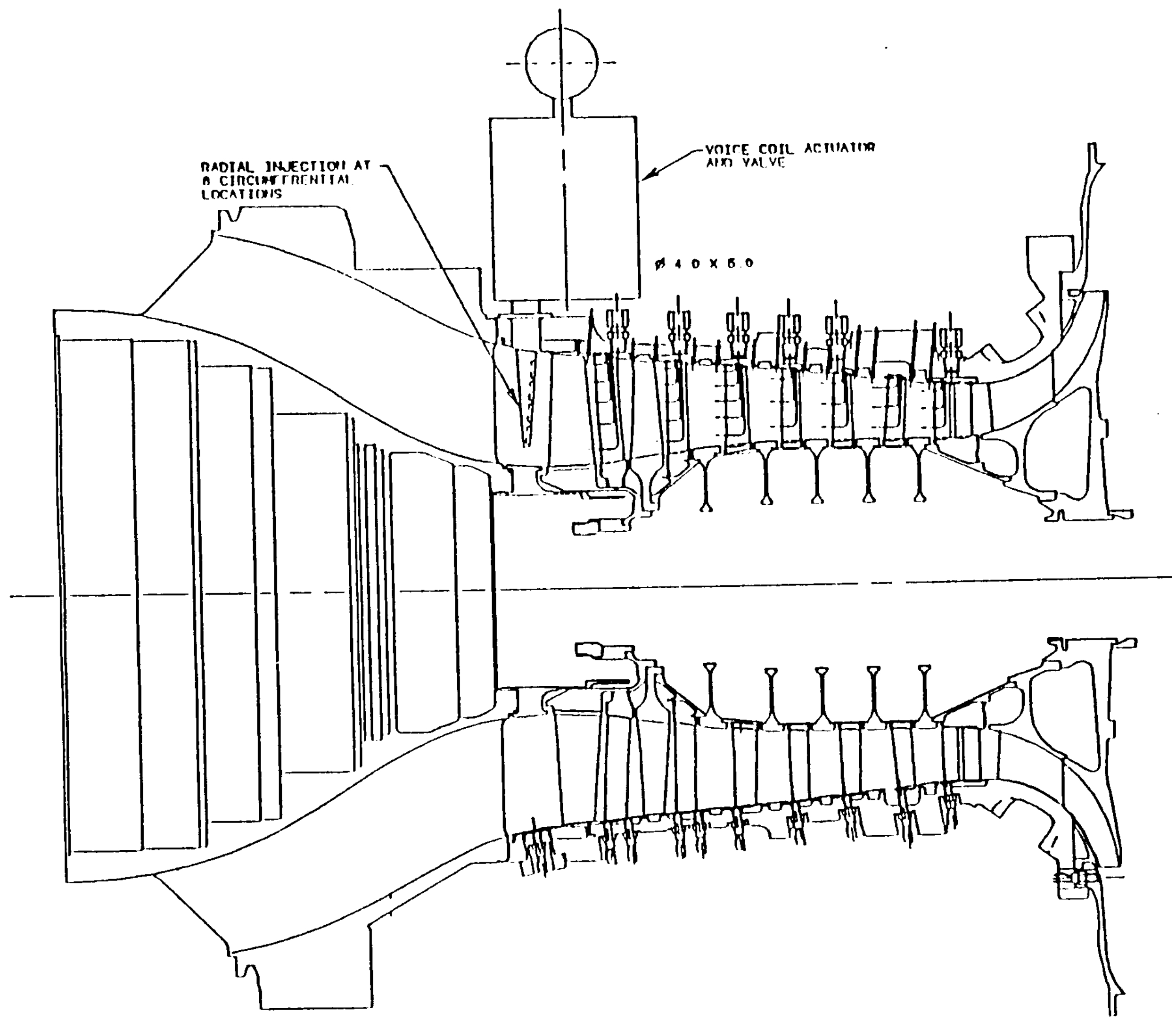
T55 COMPRESSOR MAP





ACTIVE STABILIZATION OF T55 ENGINE

TEST RIG



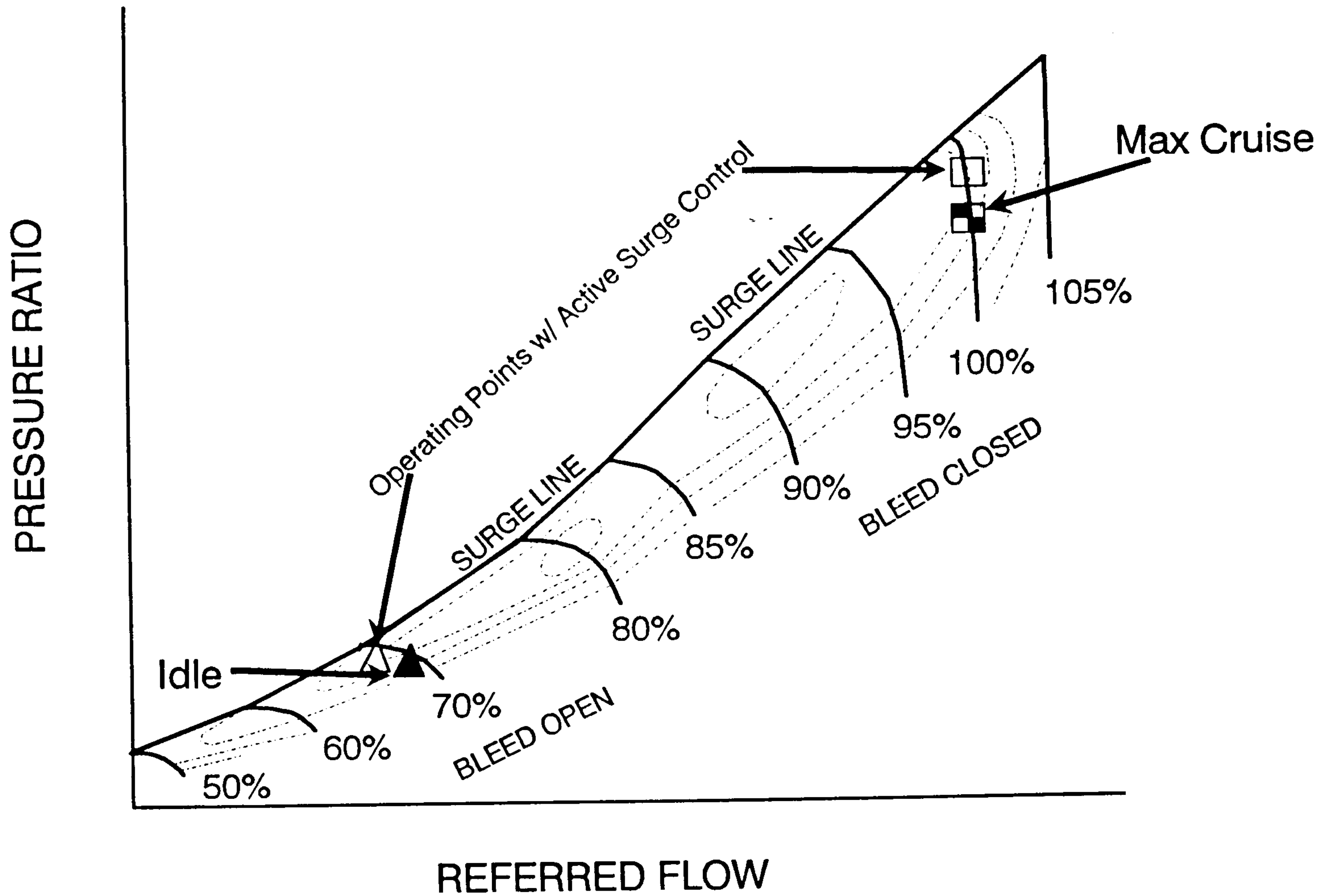
ACTIVE STABILIZATION OF T55 ENGINE

OBJECTIVE: DEVELOP AN A.S. SYSTEM FOR LOW/HIGH SPEED APPLICATION ON AN ENGINE USING AXIAL-CENT. COMPRESSOR

PROGRAM STATUS:

- RIG TESTING WITH DYNAMIC INSTRUMENTATION COMPLETED (AVPD/NASA T55 STRAT-UP STALL PROGRAM)
- DYNAMIC MODELING UNDERWAY AT MIT
- PROPOSALS SENT TO NAVY/NASA FOR A.S. SYSTEM DEVELOPMENT

COMMON CORE COMPRESSOR



ACTIVE SURGE CONTROL PAYOFFS

COMMON CORE

DESIGN POINT SFC REDUCTION: 3.3%

MAX. CRUISE SFC REDUCTION: 2.4%

IDLE FUEL CONSUMPTION = -6.6%

OPERABILITY: FROM 30 K TO 50 K FEET ALTITUDE

ACTIVE STABILIZATION OF LTS101 ENGINE

(JOINTLY SPONSORED BY NAVY)

OBJECTIVE: DEVELOP AN A.S. SYSTEM FOR HIGH SPEED OPERATION ON AN ENGINE HAVING A HIGH PRESSURE RATIO CENTRIFUGAL STAGE

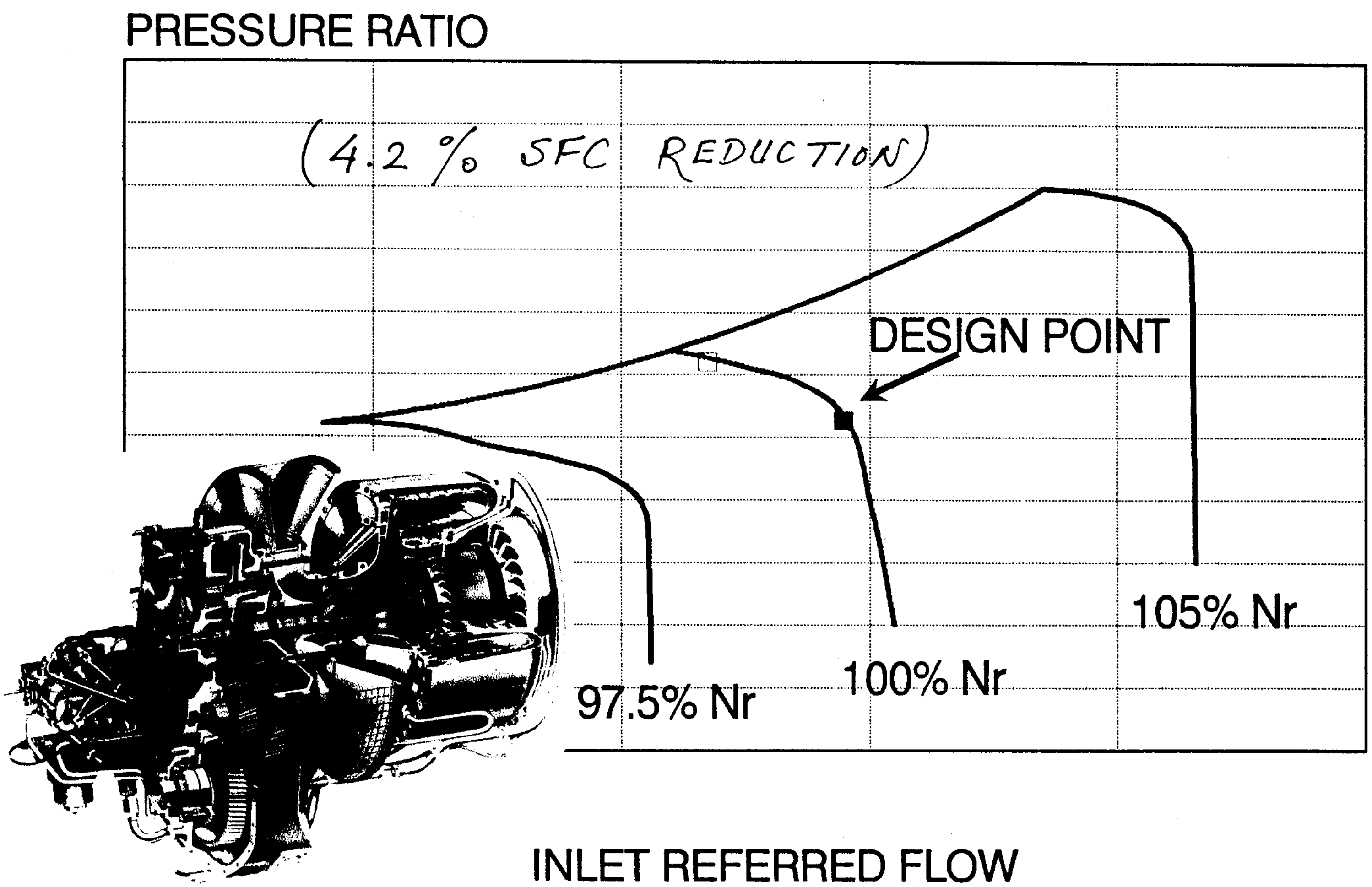
PROGRAM STATUS:

- MODIFIED AN LTS101 ENGINE FOR ACTIVE STABILIZATION APPLICATION
- DYNAMIC MODELING COMPLETED
- FORCED RESPONSE TESTING USING INBLEED AT ROTOR INLET COMPLETED
- FORCED RESPONSE TESTING USING THROAT INBLEED UNDERWAY

LTS101 COMPRESSOR

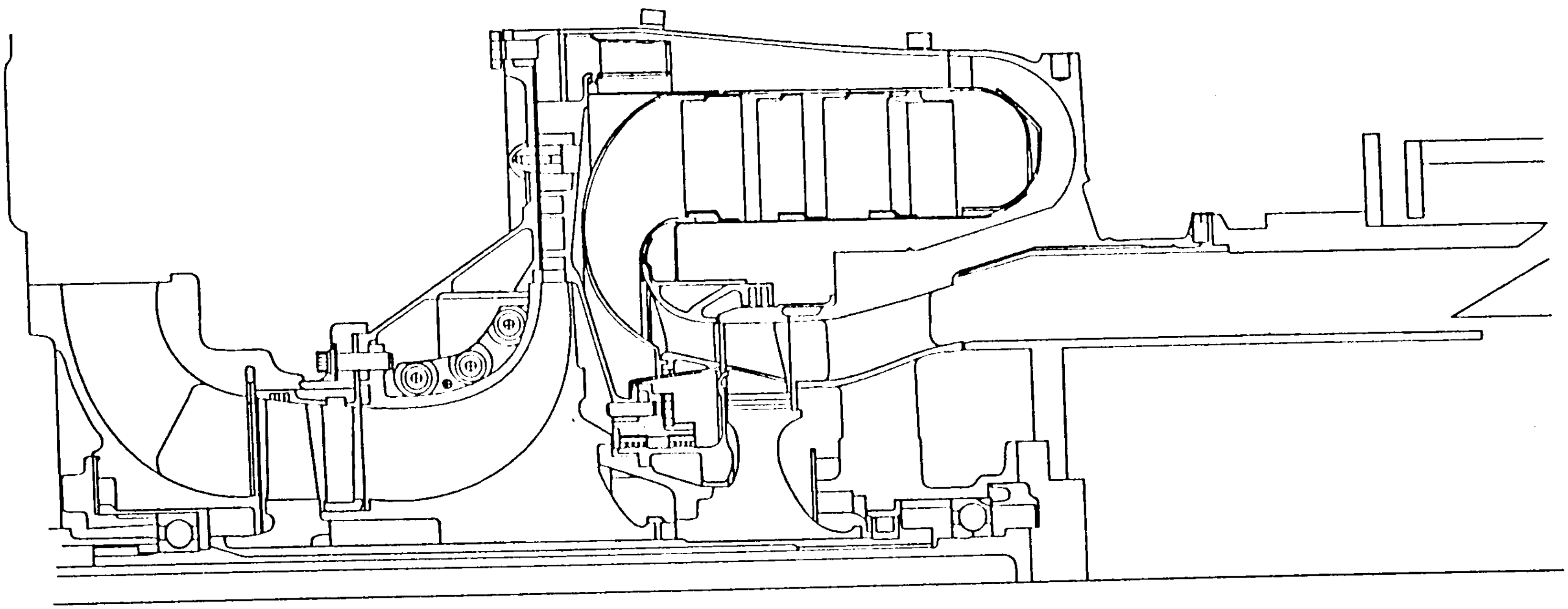
4.0 % SAVING IN IDLE FUEL CONSUMPTION

3.7 % INCREASE IN SPECIFIC POWER



ACTIVE STABILIZATION OF LTS101 ENGINE

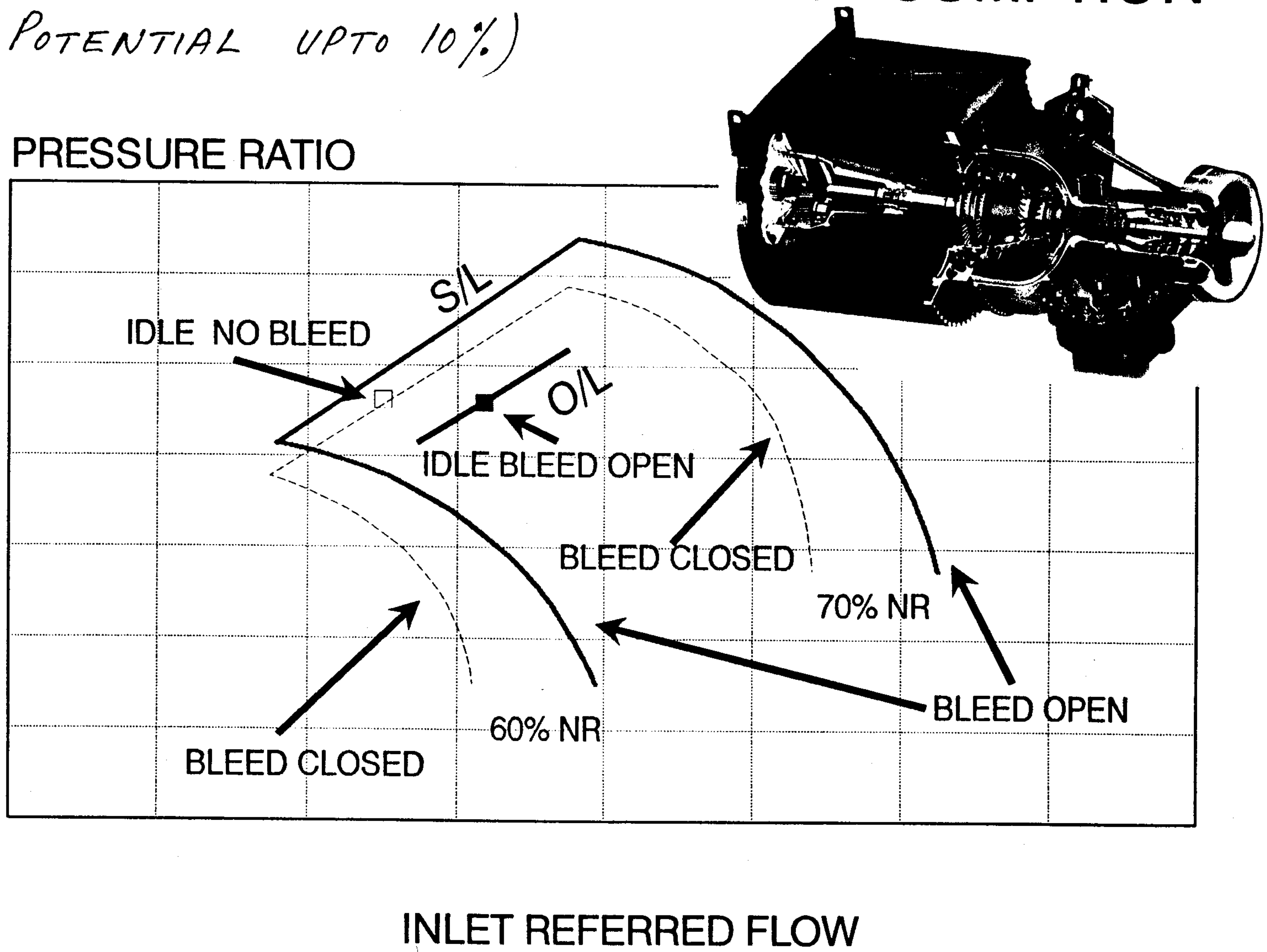
TEST RIG



AGT 1500 HIGH PRESSURE COMPRESSOR

2.6 % SAVING IN IDLE FUEL CONSUMPTION

(POTENTIAL UPTO 10%)



ACTIVE STABILIZATION

ISSUES AND CONCERNS

SEVERAL UNKNOWNS ABOUT ACTIVE STABILIZATION SYSTEM:

- EFFECTIVENESS IN ENGINE ENVIRONMENT
- RELIABILITY
- ACTUATOR DEVELOPMENT SCHEDULE
- DEVELOPMENT COST AND SCHEDULE
- PRODUCTION COST
- WEIGHT

CONCLUDING MESSAGE

AN EARLY CONCEPT DEMO ON AN ENGINE IS VERY IMPORTANT PRIOR TO A MAJOR INVESTMENT BY ENGINE COMPANIES

AND

BASIC RESEARCH MUST CONTINUE

MIT RESEARCH IN ACTIVE COMPRESSOR STABILIZATION

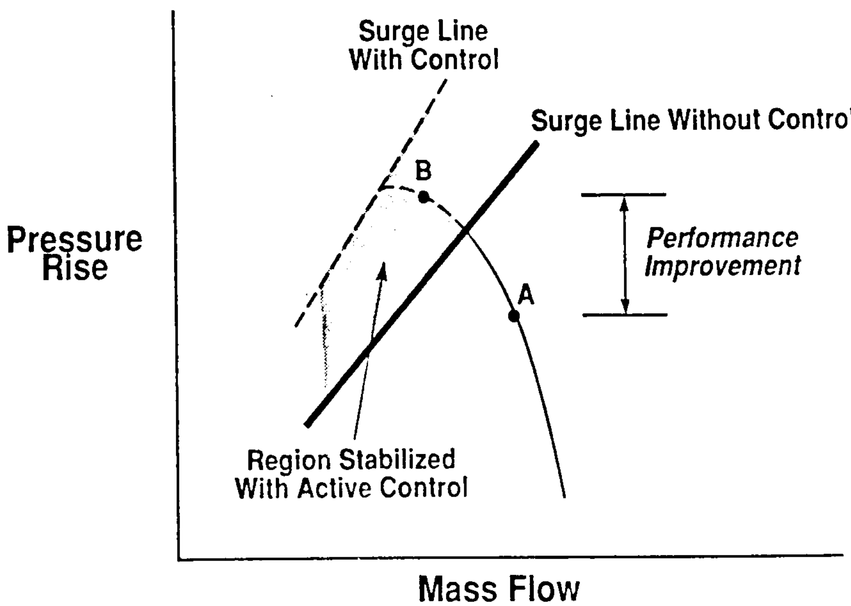
Presented to the Workshop on
Intelligent Turbine Engines for Army Applications
March 21-22, 1994

A. H. Epstein E. M. Greitzer G. R. Guennette J. D. Paduano C. S. Tan

OUTLINE

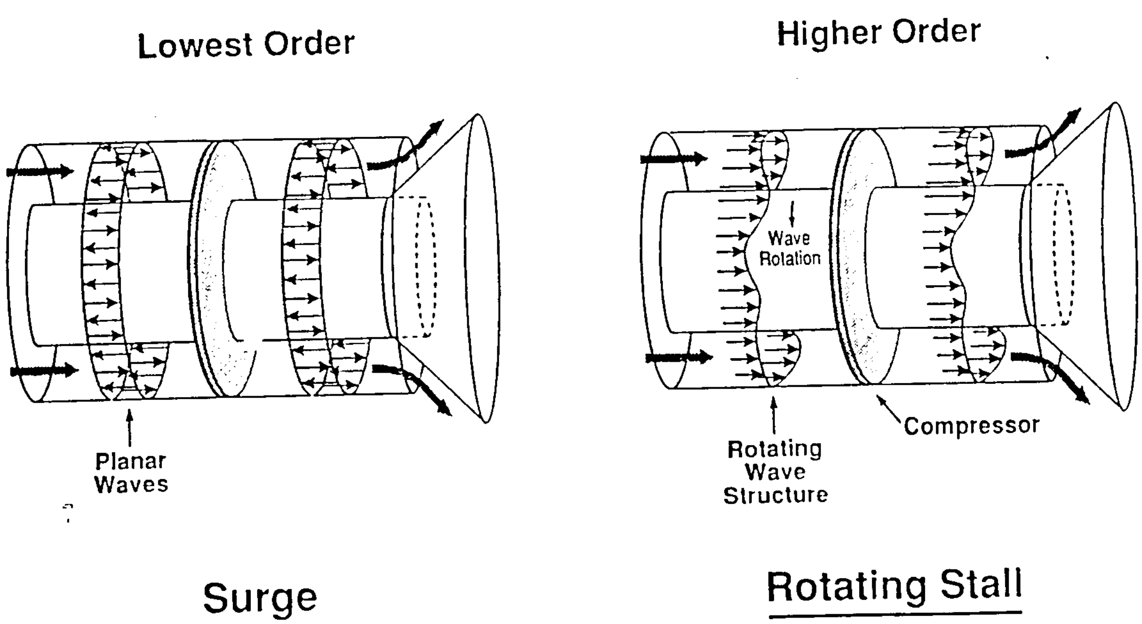
- Background
  - Goal of Active Control
  - Surge and Rotating Stall in Compressors
- Surge Control
  - Results - High-Speed Centrifugal Turbocharger
  - Current Research - Centrifugal Gas Turbine Surge Control
- Rotating Stall Control
  - Results in Low Speed Axial Compressors
  - Modeling and Detection in High Speed Compressors
  - Current Research in Control of R/S in High Speed Compressors

GOAL OF ACTIVE STABILIZATION
- Safe Operation at Higher Performance Levels -



- System study projects 8% reduction in GTOW or 11% longer range

NATURAL OSCILLATORY MODES OF COMPRESSORS

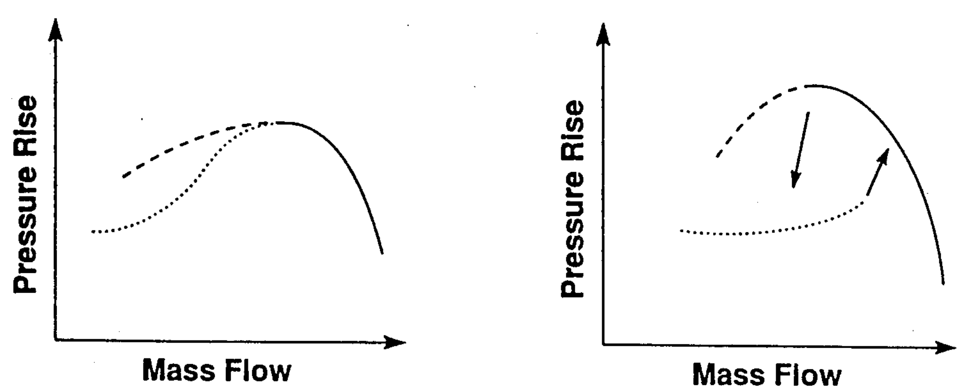


SURGE AND ROTATING STALL IN GAS TURBINES

- Rotating Stall Generally Precedes Surge
  - Often eventually leads to surge
- Depending on Machine, May Choose to Control Surge and Not R/S
  - Centrifugals, axicentrifugals: surge control alone may pay off
    - rugged compressors
    - 'progressive', recoverable rotating stall
    - surge is first debilitating instability
  - Axial, multistage compressors - R/S control required
    - rotating stall is abrupt, debilitating
    - control surge alone ⇛ deep, nonrecoverable stall

COMPARISON OF RECOVERABLE AND DEEP ROTATING STALL

—— Compressor test, *no surge*
- - - - Unstable axisymmetric map, *no rotating stall*
.... Rotating stall



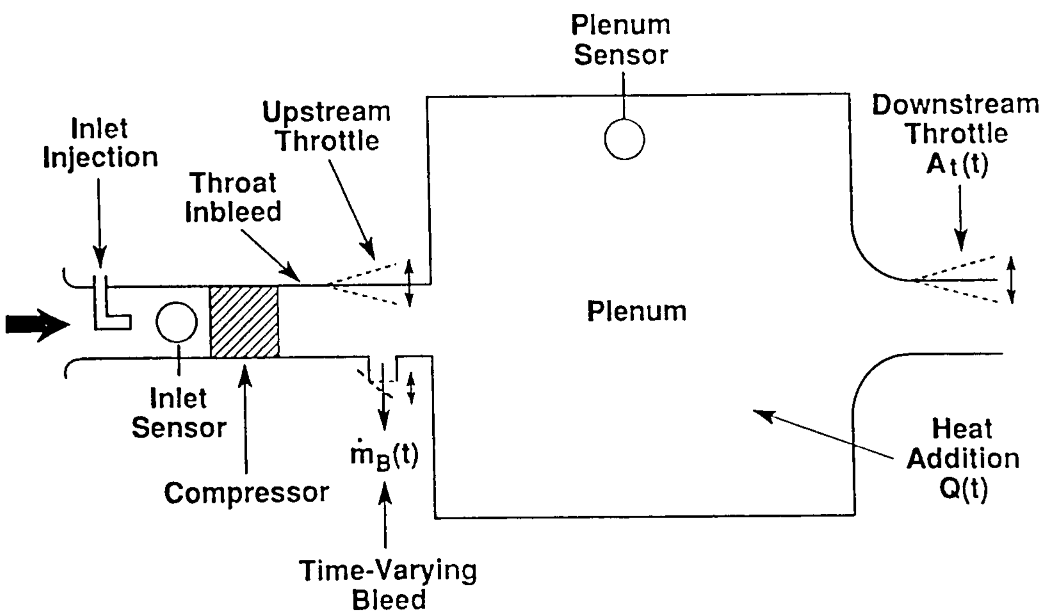
Centrifugal Compressors, Fans, and Blowers

Axial Compressors

EARLY SURGE CONTROL RESULTS

- Rig Demonstration (Pinsely et al., 1988)
  - High speed (90,000 Rpm) centrifugal supercharger
  - 100 Hz valve actuating downstream or plenum bleed
  - Demonstrated 20-25% operating range extension
- Dynamic Control Trough Tailored Structures (Gysling, 1991)
  - Movable plenum wall w/ tailored structural dynamics
  - Tuned to act as passive damper for surge oscillations
  - Demonstrated 25% operating range extension
- Detailed Sensor/Actuator Placement Studies (Simon, 1991)
  - Sensor and actuator type, placement are pivotal
  - Close-coupled actuation is a key to success
  - Highly multidisciplinary endeavor

STUDYING ALTERNATE IMPLEMENTATION STRATEGIES

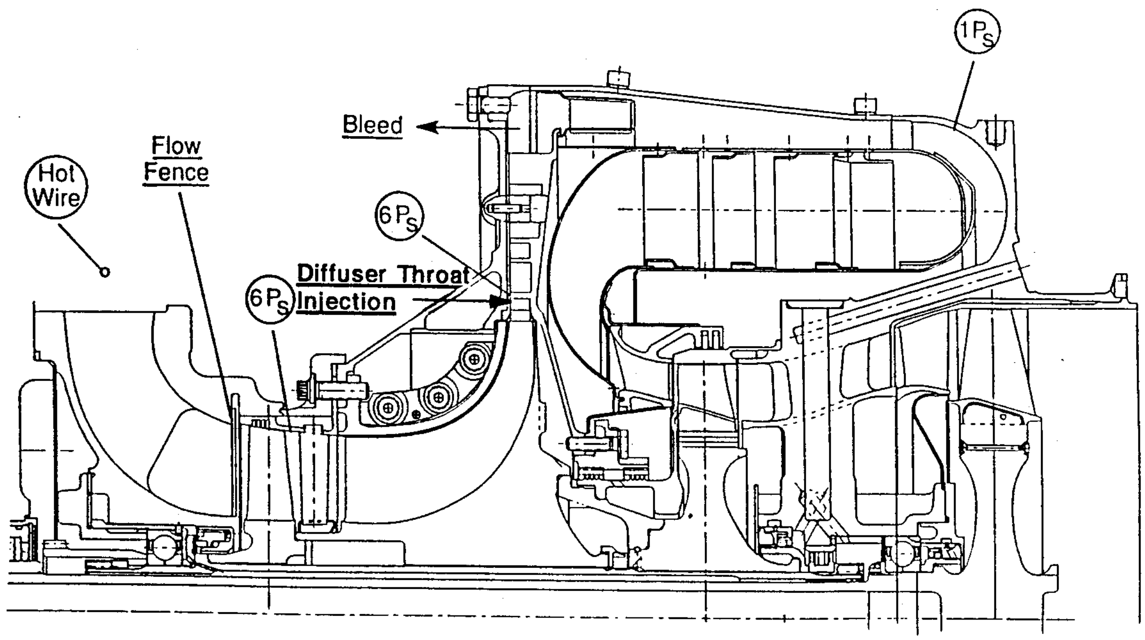


Integrates control theory, engine design, fluid mechanics, experimentation, aeroelastics

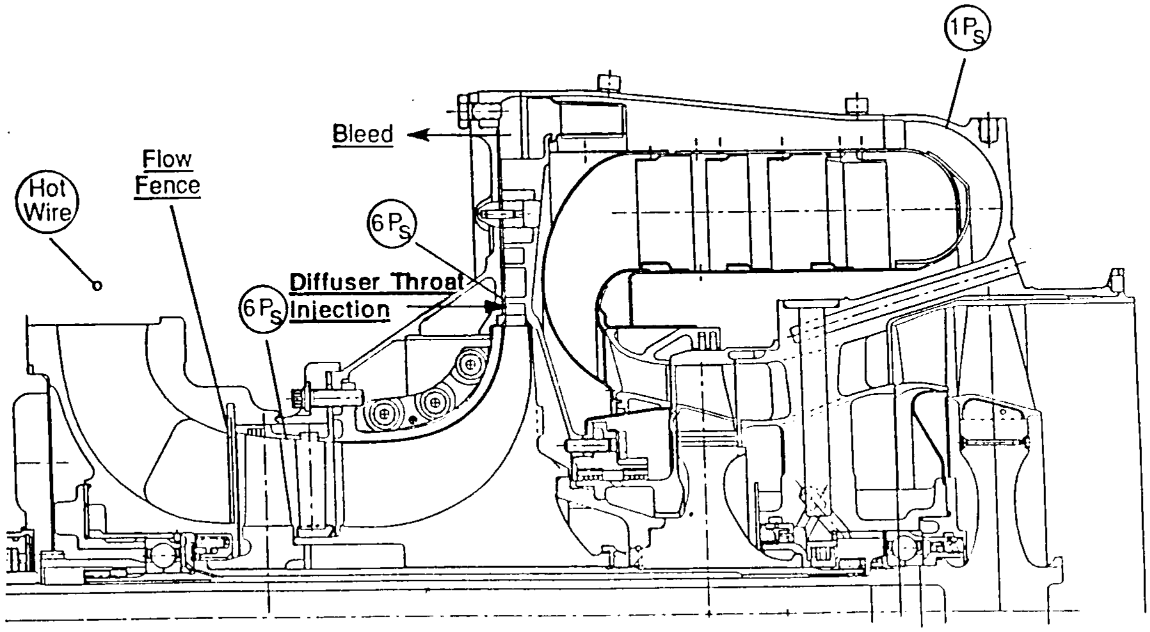
CURRENT EFFORTS - ACTIVE SURGE STABILIZATION IN SMALL GAS TURBINES

- Two 650 HP engines on test stands
  - Textron LTS-101 gas producer (turbojet w/ variable area nozzle)
  - Allison 250-C30 turboshaft (power turbine and water break)
- Surge Model Extended to Include:
  - Combustor energy dynamics
  - Compressor/turbine shaft dynamics
  - Compressibility
  - Candidate actuation strategies
- Sensor/Actuator Effectiveness Study Complete
  - Diffuser throat injection very promising
  - Fuel modulation least effective
- LTS-101 Modified for Diffuser Throat Injection

LTS-101 INSTRUMENTATION LAYOUT



LTS-101 INSTRUMENTATION LAYOUT



GAS TURBINE PRESENTS NEW CHALLENGES TO ACTIVE CONTROL DESIGN/MODELLING

__Turbocharger System__

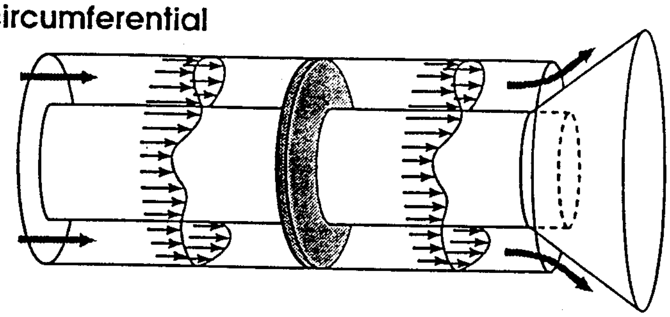
- $\pi_C \sim 2, M_T \sim 0.8$
- Simple compact geometry
- "Shallow" characteristics
- Low Helmholtz frequency

__G.T. Helicopter Engine__

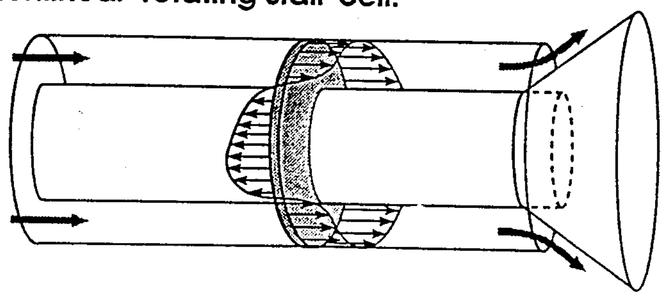
- $\pi_C \sim 8, M_T > 1.0$
- Complex geometry
- "Steep" characteristics
- High Helmholtz frequency
- Combustion
- Shaft dynamics
- Very noisy

ROTATING STALL
A Distributed Fluid-Mechanical Instability

Small amplitude circumferential traveling waves:

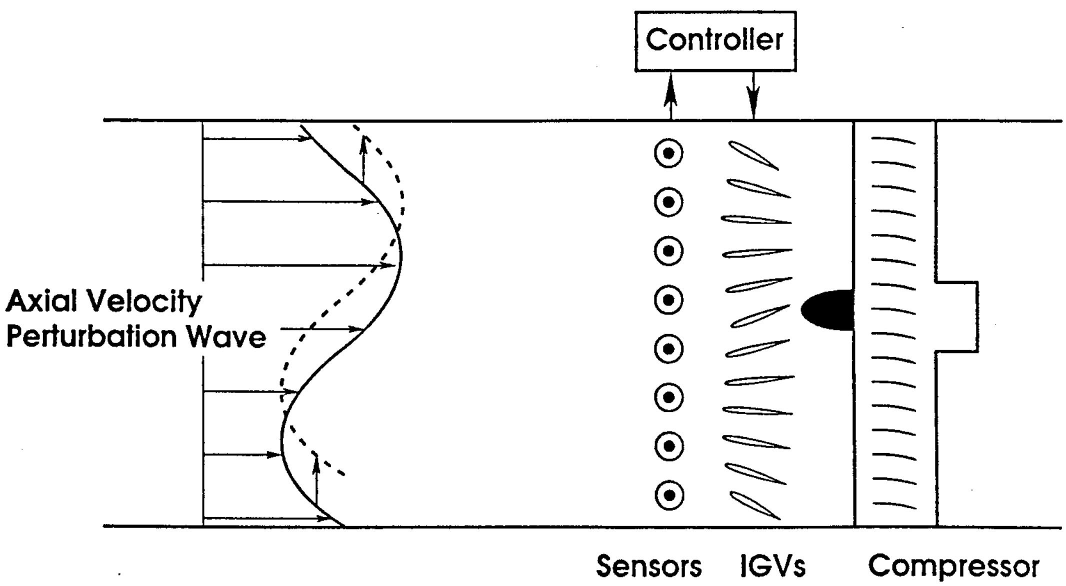


Large amplitude nonlinear 'rotating stall' cell:



- Rotating Stall Causes Damage, Leads to Surge
- Engine Performance Compromised to Avoid Stall/Surge

ROTATING STALL STABILIZATION
"Distributed" Sensors and Actuators

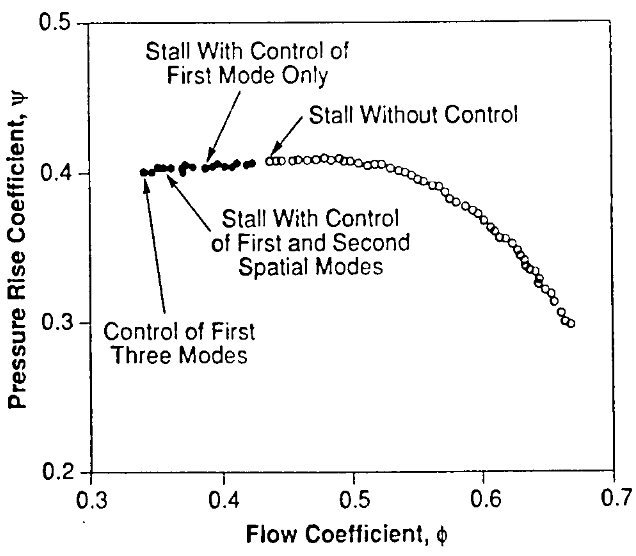


- stator vanes (IGVs) individually servo-controlled
- wave stabilization increases compressor operating range

ROTATING STALL CONTROL DEMONSTRATIONS
- Low Speed Compressors -

- Single-Stage Axial
  - Original demonstration
  - Modeling, identification, and control concepts & techniques developed
- Three-Stage Axial
  - Verification of 1-stage results on Pratt-designed rig
  - Detailed identification, refinement of fluids models
  - Testbed for advanced modeling and control
- Dynamic Control Using Aeromechanical Feedback
  - Tailored structures coupled to fluid mechanics
  - Proof of passive control concept
  - Close-coupled actuation concept tested

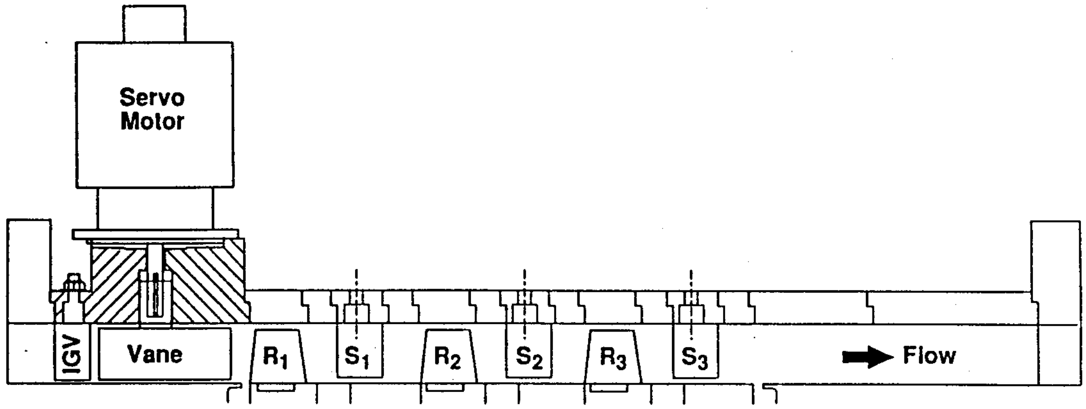
SINGLE-STAGE DEMONSTRATION
18% Operating Range Increase with Active Control



-Control Circumferential Harmonics Independently
Moore-Greitzer dynamics borne out

-Additional Range For Each Addt'l Harmonic

ACTIVELY STABILIZED THREE-STAGE COMPRESSOR



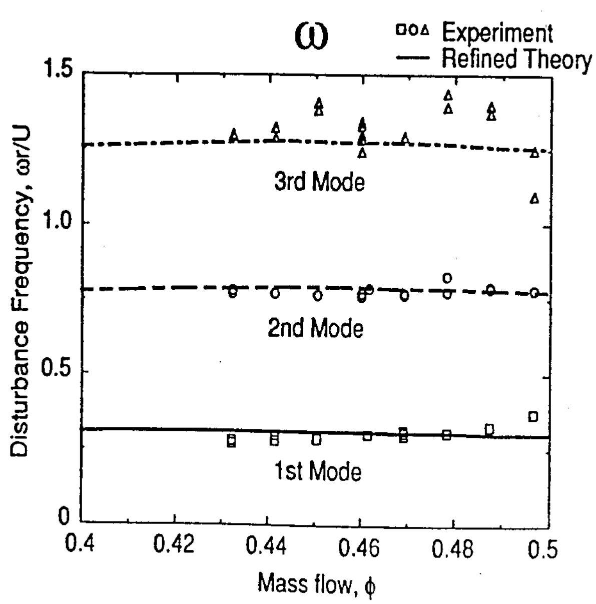
Design Characteristics:

Low Speed	ω = 2400 RPM	$\phi = C_x/U = 0.6$
High Reaction	R = 0.74	
No Surge	B = 0.16	

PARAMETER IDENTIFICATION RESULTS
and
Refined Theoretical Predictions

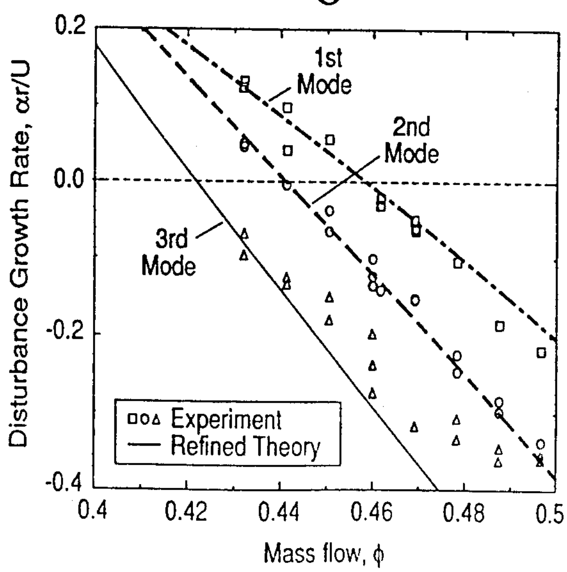
rotation rate

ω

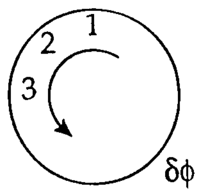


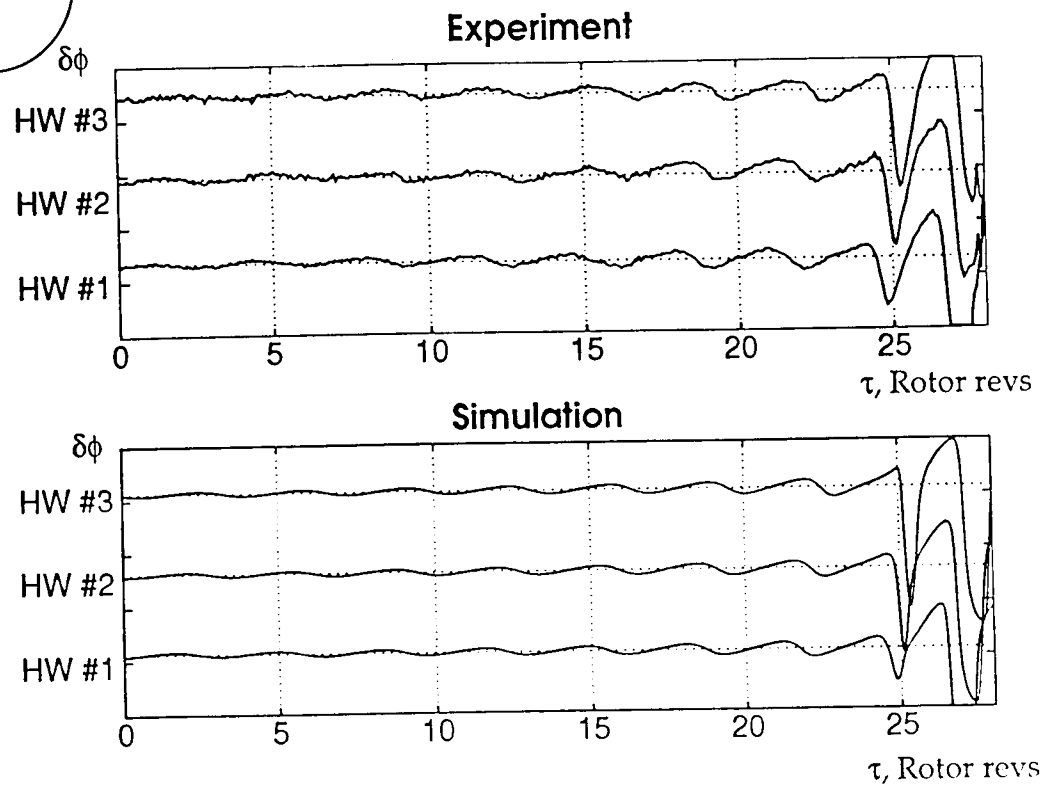
growth rate

σ



NONLINEAR MODEL VALIDATED AGAINST STALL INCEPTION DATA

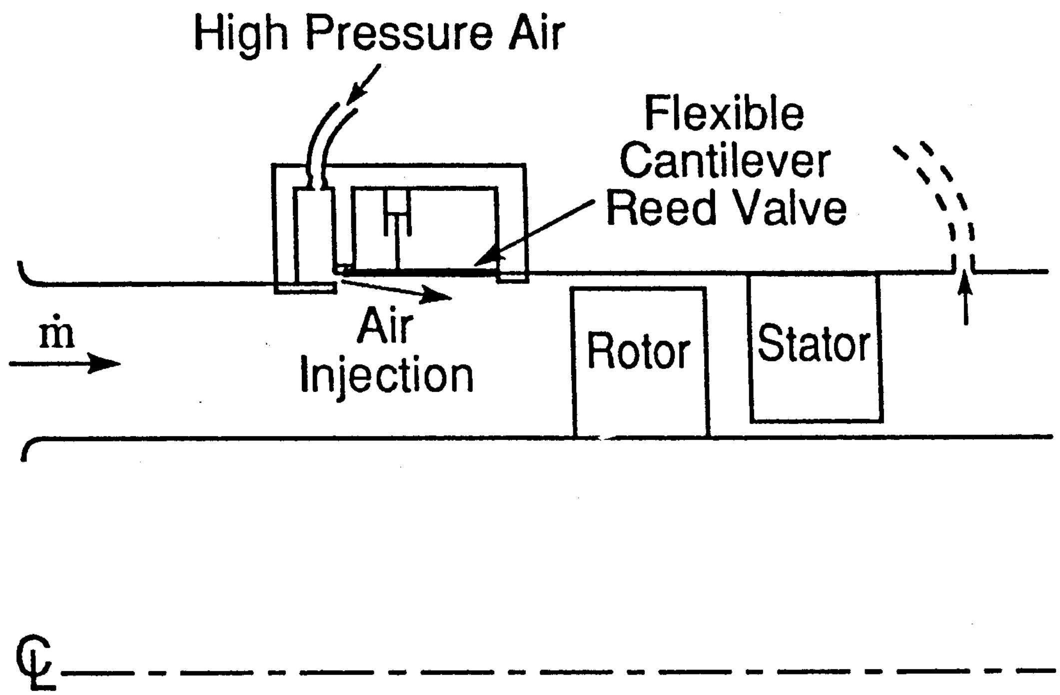




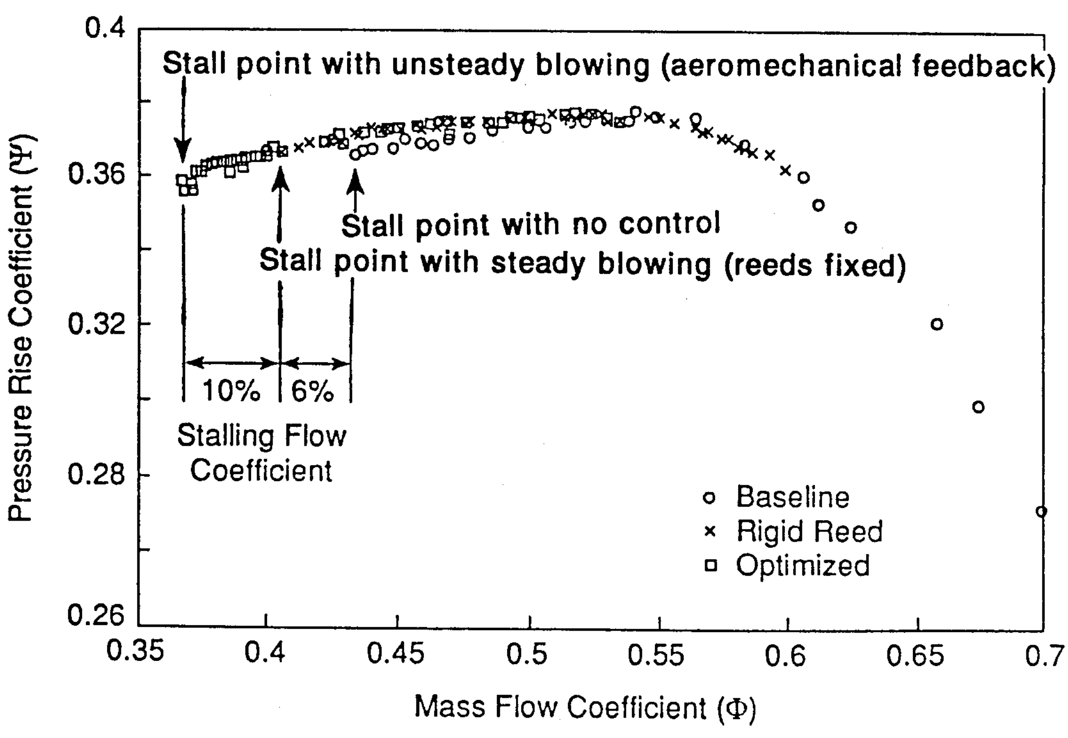
AEROMECHANICAL CONTROL OF ROTATING STALL

- 'Passive' system
  - Feedback through dynamic coupling between unsteady flow and structure
- Deflection of structure causes flow injection into annulus
- Circumferential array of 24 reed valves control injection
- Phase of injection set by interaction between stall precursors (pressure perturbations) and reed dynamics
- 10% change in stall point

DYNAMIC CONTROL OF ROTATING STALL USING AEROMECHANICAL FEEDBACK



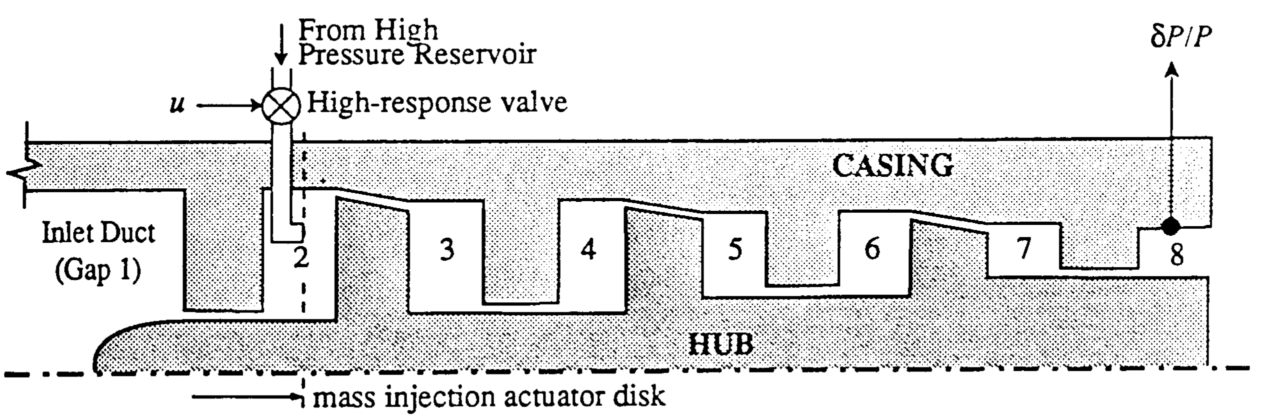
RANGE INCREASE DUE TO AEROMECHANICAL FEEDBACK



HIGH SPEED COMPRESSOR STALL CONTROL RESEARCH

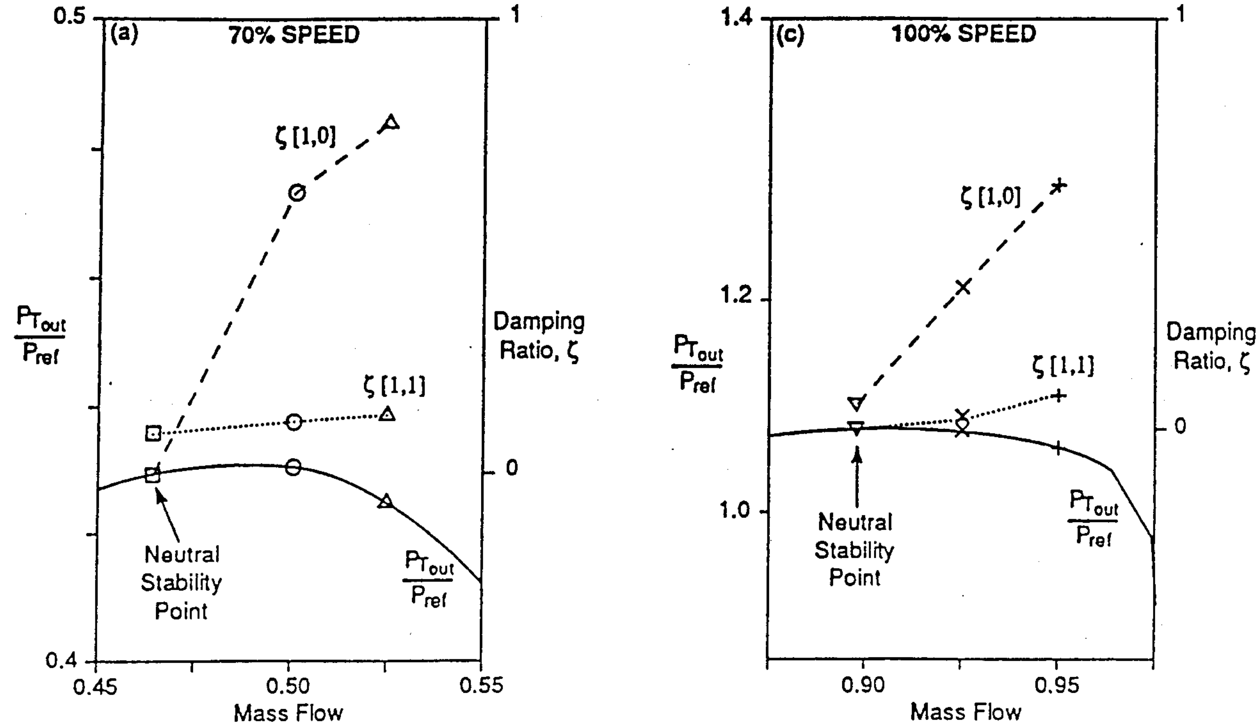
- Modeling
  - Compressible 2D Hydrodynamic Stability Model In Place
  - Applied to Industrial Compressor Test Rig Geometries
  - Compressible Modes Explain Experimental Results
  - Control, Sensor/Actuator Studies Underway
- Detection
  - Data from 10 high speed compressors reduced
  - Pre-stall traveling wave energy present in all cases
  - 'Compressible mode' important to stall inception
- Actuation
  - Mass injection currently the most promising
  - Valve hardware designed (Moog and NASA Lewis)
  - Currently Investigating fluid mechanics of unsteady blowing
- Initial Control Design Studies Underway

COMPRESSIBLE MODELING OF ROTATING STALL

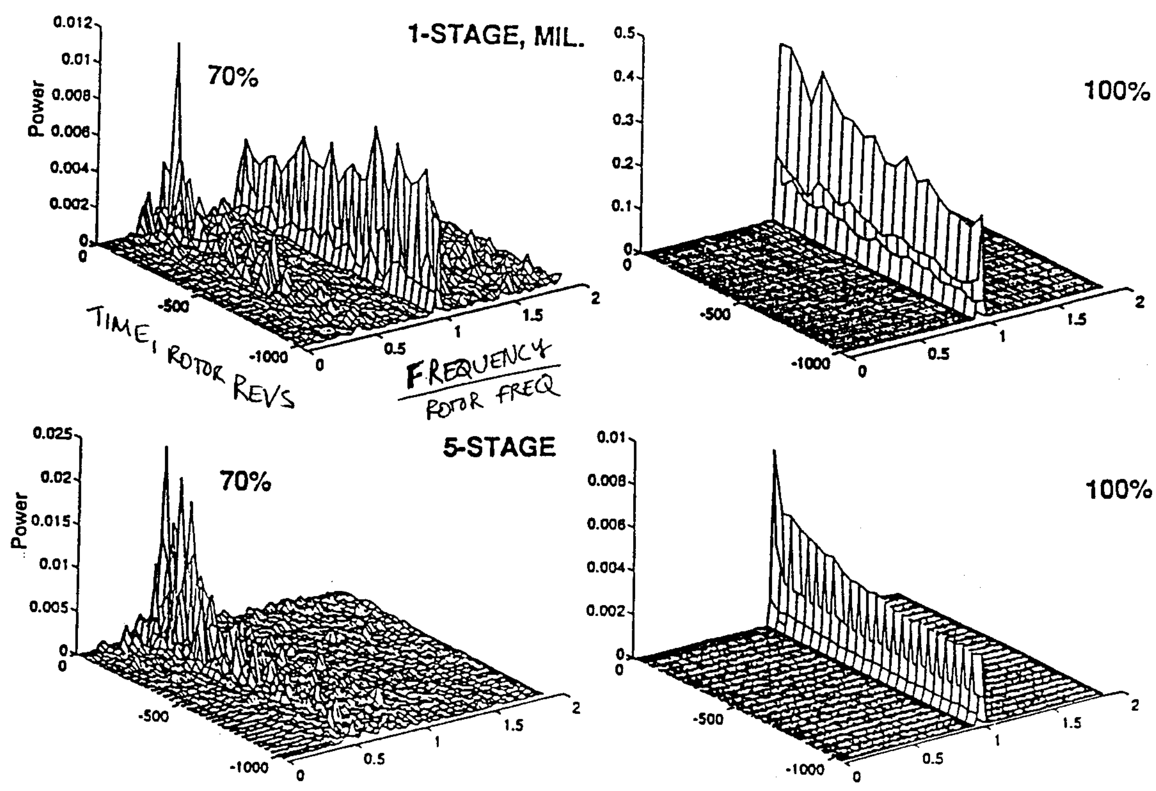


- 1D Compressible Flow in Blade Passages
- 2D Compressible Flow in Gaps
- Boundary Conditions Link Volumes
- Result - Hydrodynamic Model for Circumferential Harmonics
- Actuation and Sensing Added to Study Control

MODEL PREDICTS
COMPRESSIBLE MODE AT ROTOR FREQUENCY
- this mode can limit operating range -



HIGH SPEED COMPRESSOR PRE-STALL SPECTRA



CURRENT EFFORTS - ACTIVE CONTROL OF ROTATING STALL

- Control With Inlet Distortion on 3-Stage Rig
  - High priority for implementation
  - Modeling, control much more complicated
  - We will 'close the loop' with distortion this Spring
- Mass Flow Injection on 3-Stage Rig
  - Replace inlet guide vanes with injectors
  - Significant performance improvement predicted by 2D modeling
  - Details of implementation will effect performance achieved
- Application of Advanced Control Techniques
  - Robust controller design and implementation
    - demonstrated on 3-stage
    - developing techniques for use at NASA Lewis
  - Nonlinear analysis and control law design
    - goal: enhance large disturbance stability
    - applying Lyapunov, absolute stability theory

CURRENT EFFORTS - ACTIVE CONTROL OF ROTATING STALL - NASA Lewis Project -

- Industrial scale compressor stages
  - Stage 37 - High speed compressor stage (U_{tip}= 454 m/s, h/t=.7)
  - Stage 67 - Low hub/tip fan stage (U_{tip}= 430 m/s, h/t=.36)
- Mass flow injection, high-bandwidth actuation (300-500 Hz)
  - NASA Lewis & Moog designing linear actuators
  - MIT designing valves and injectors
  - Scale wind tunnel tests (M=0.5) of injection underway
- 3D hydrodynamic stability analysis of rotating stall
- System procedures for eigenvector identification
- Testing at NASA to begin Late 1994

SUMMARY
Stall and Surge Control are Maturing Rapidly

- Evolution of apparatus complexity

    Surge control concept ⇒ surge rig ⇒ small engines

    R/S control concept ⇒ 1 stage ⇒ 3 stage ⇒ high speed/industrial

- Evolution of maturity of understanding

    - Surge control:

        Lumped model ⇒ model w/ actuation ⇒ engine scale, environment

    - Rotating stall control:

        Moore-Greitzer ⇒ unsteady losses ⇒ distortion ⇒ high speed, 3D, nonlinear

- Each evolutionary stage has been successful to date

    - Still *much* to do, but confidence is high

- New multidisciplinary concepts are emerging *out of necessity*:

    'Close-coupled' actuation

    System identification of fluid processes

    Passive aeromechanical control

    Wave energy for detection

    Interaction of compressible and acoustic modes

Progress in Modeling & Control of Compressor Stall

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Intelligent Turbine Engines for Army Applications
Cambridge, MA (MIT)
March 21, 1994

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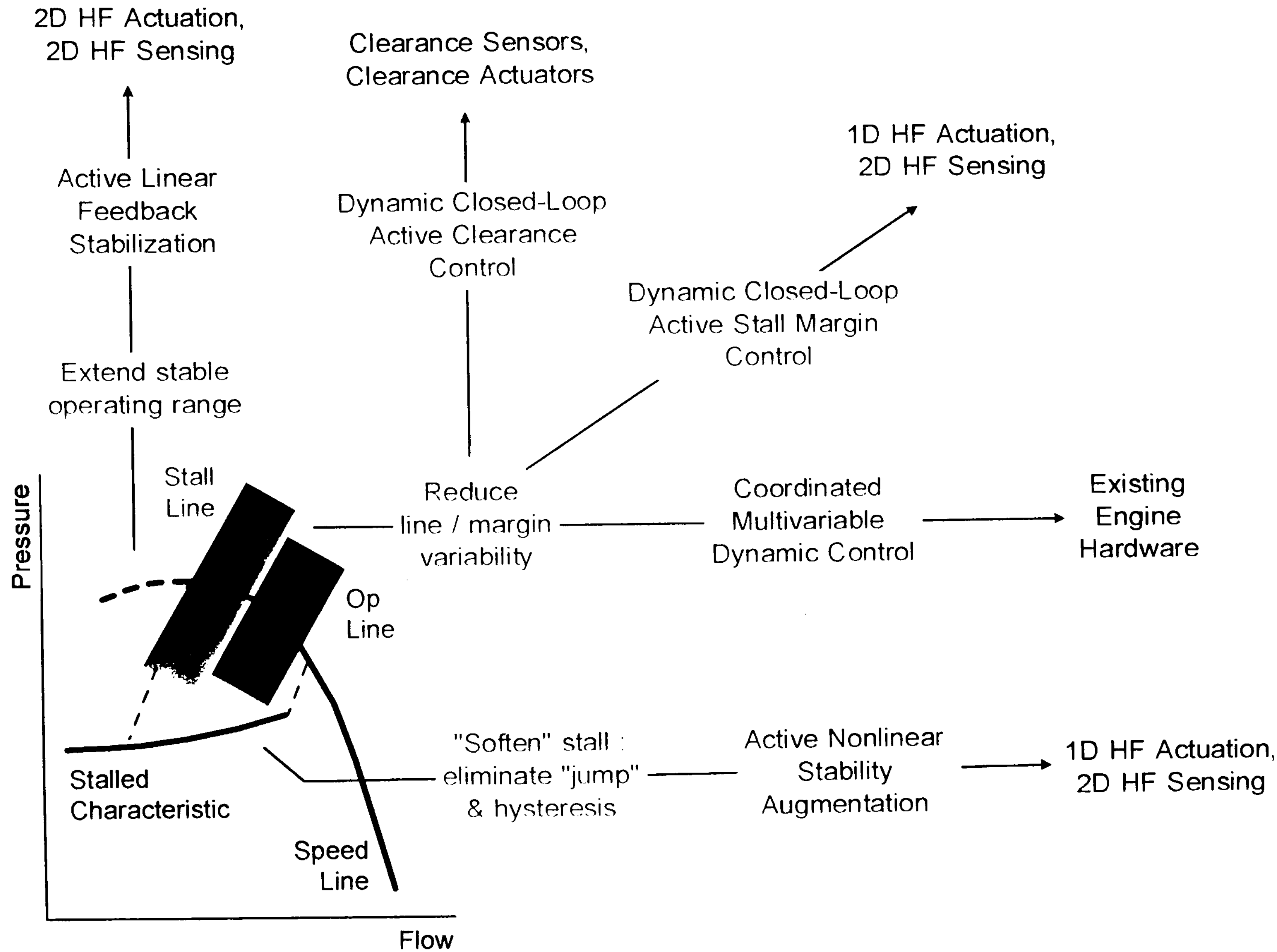
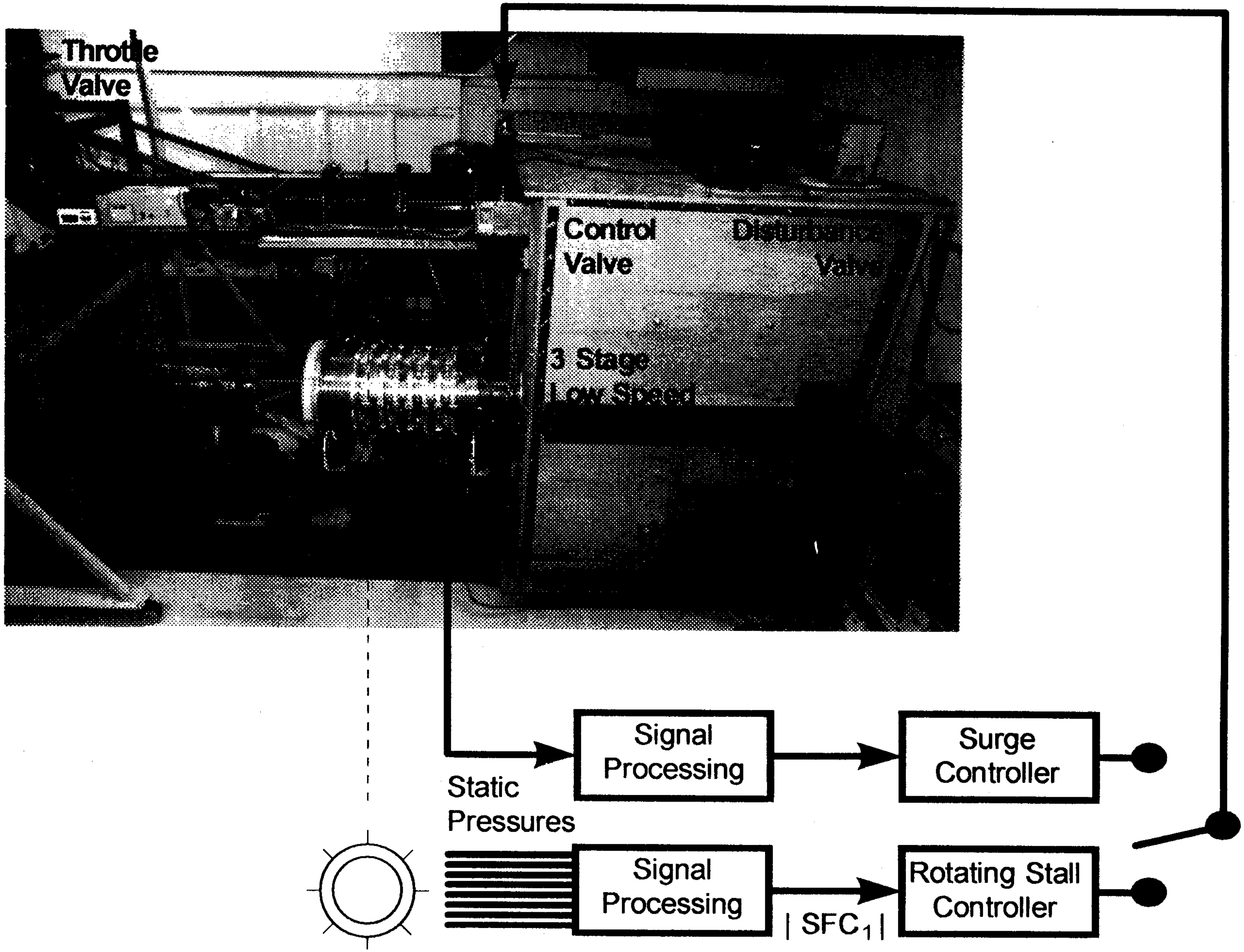
Obstacles and Related Issues

- Highly nonlinear phenomena characterized by bifurcations
  - relevancy of linear perspective
- 3D distributed unsteady compressible flow phenomena
  - model uncertainty (unknown physics and parameters)
  - model complexity
  - number, locations, and types of actuators and sensors
- Relatively high frequency phenomena
  - sensor and actuator bandwidths
  - digital processor throughput
- Inherently noisy and hostile operating environment
  - sensing and actuation constraints
- Complex interactions with overall system and operating environment

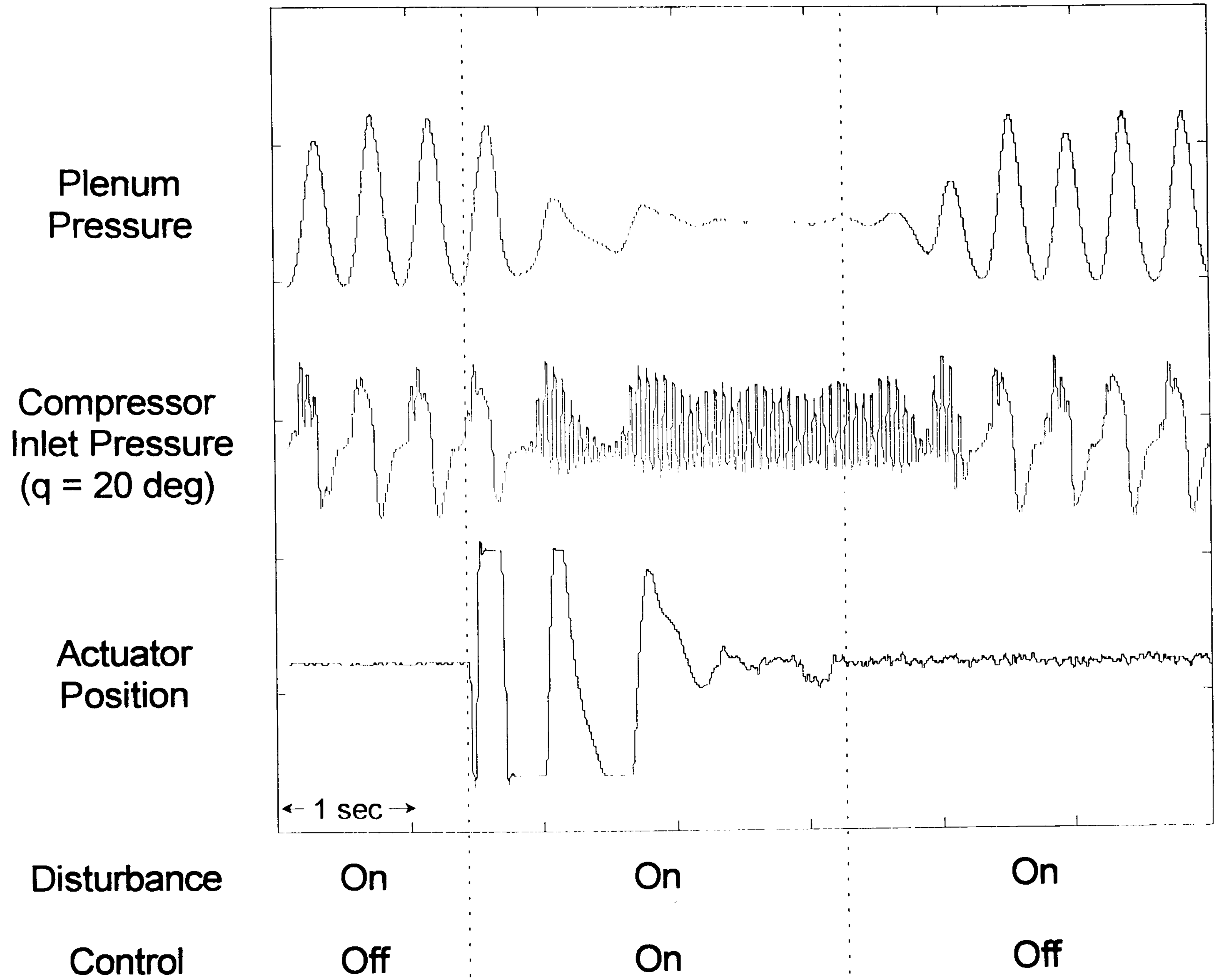
Stability Enhancing Control Concepts



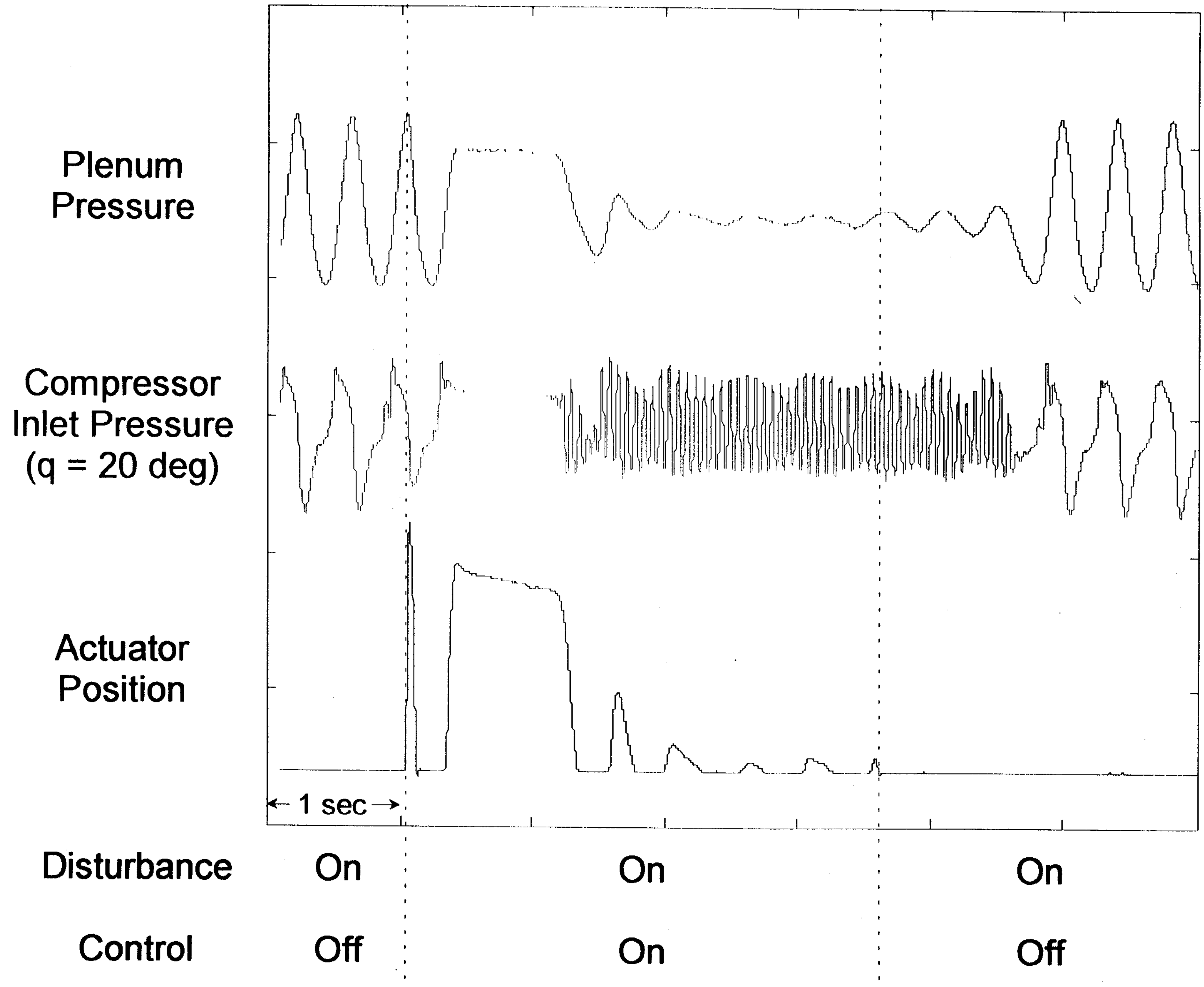
Active Control Proof-of-Concept Demos



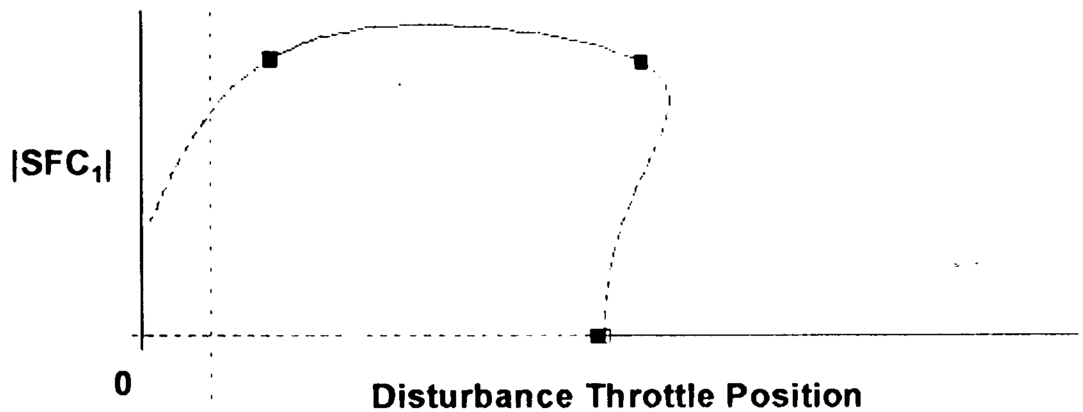
Active Surge Control Demo: 2-Way Actuation



Active Surge Control Demo: 1-Way Actuation



Active Surge Control Demos



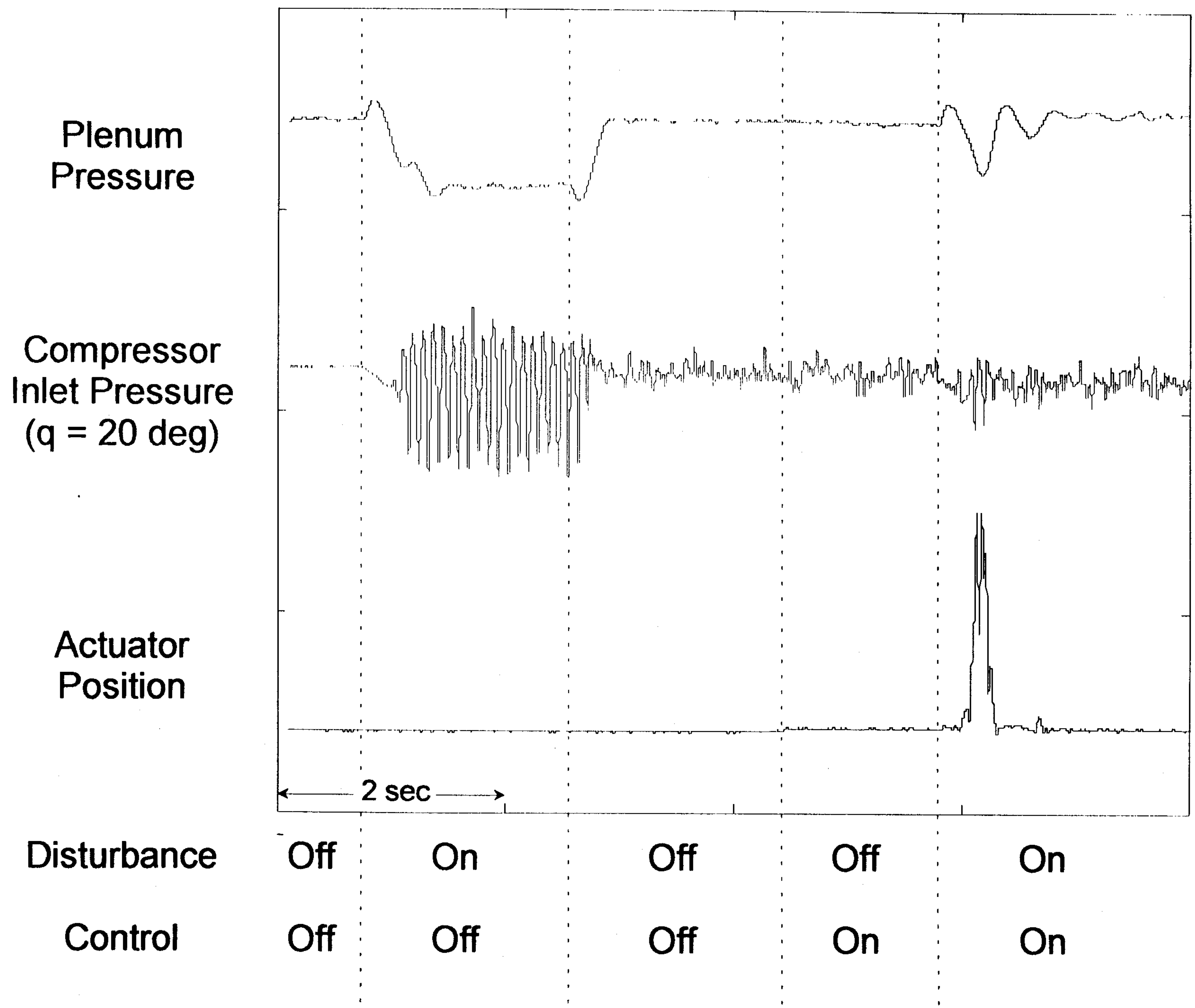
control off

previously unstable
equilibrium stabilized

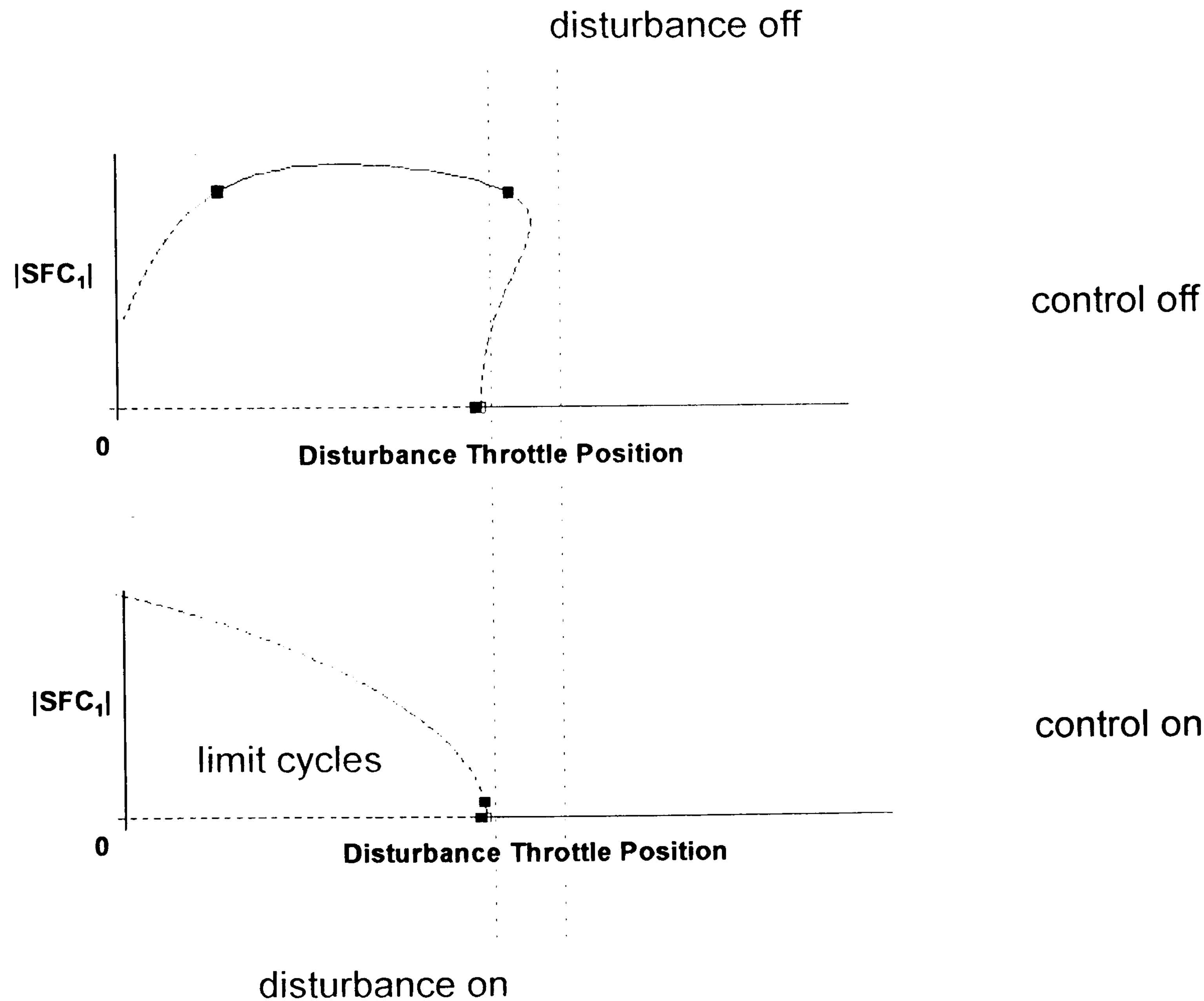
control on

disturbance on

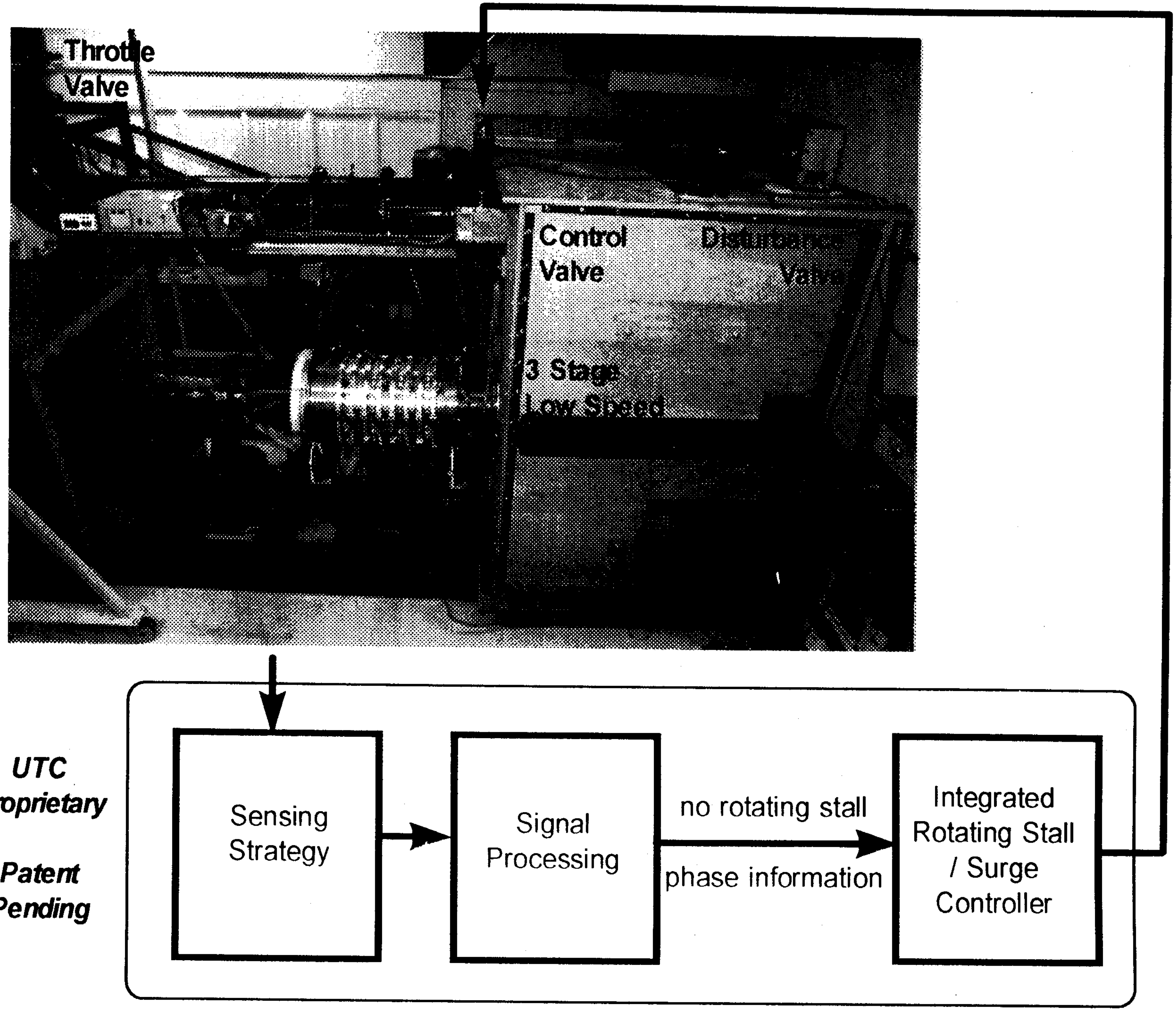
Active Rotating Stall Control Demo



Active Rotating Stall Control Demo



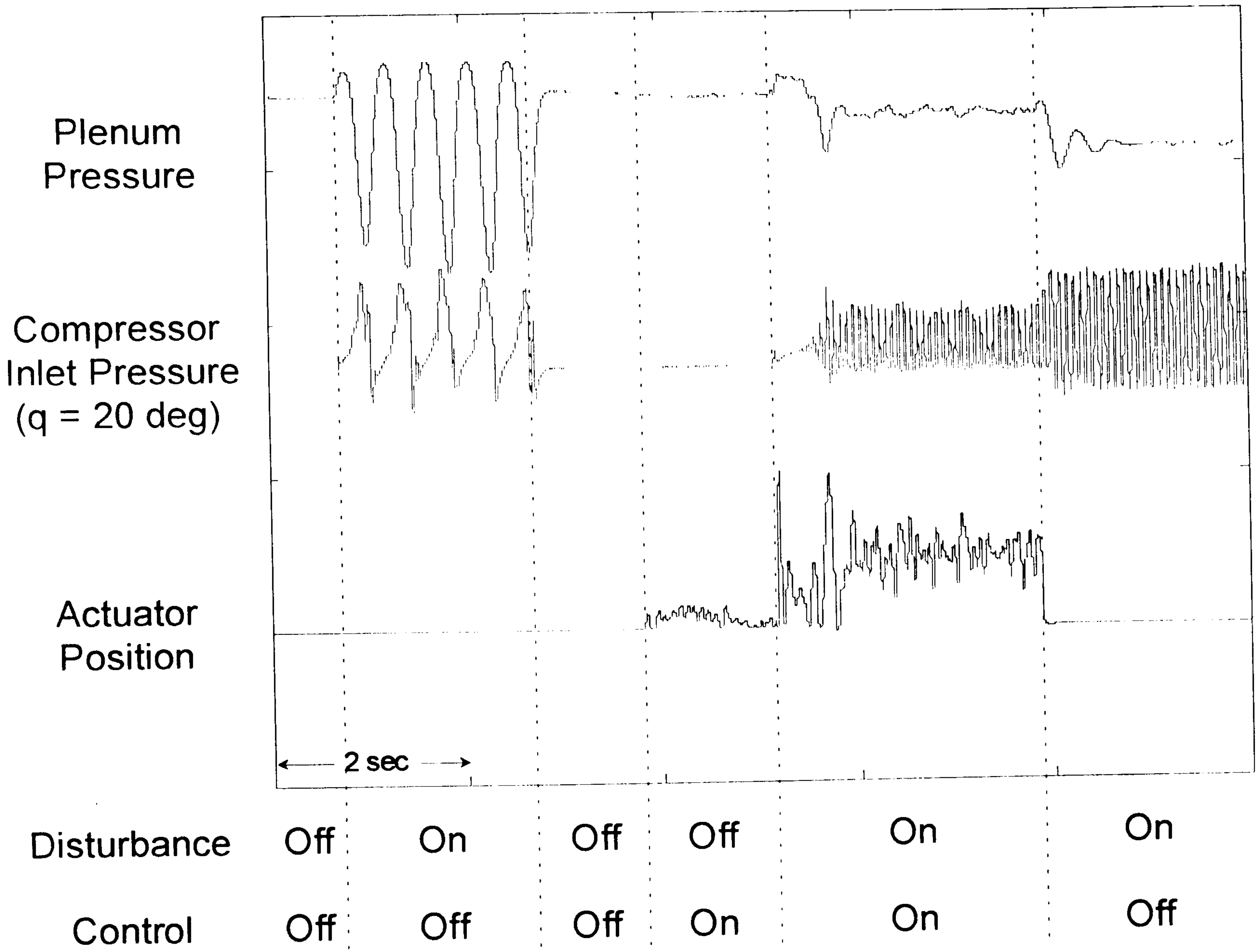
Integrated Control Proof-of-Concept Demo



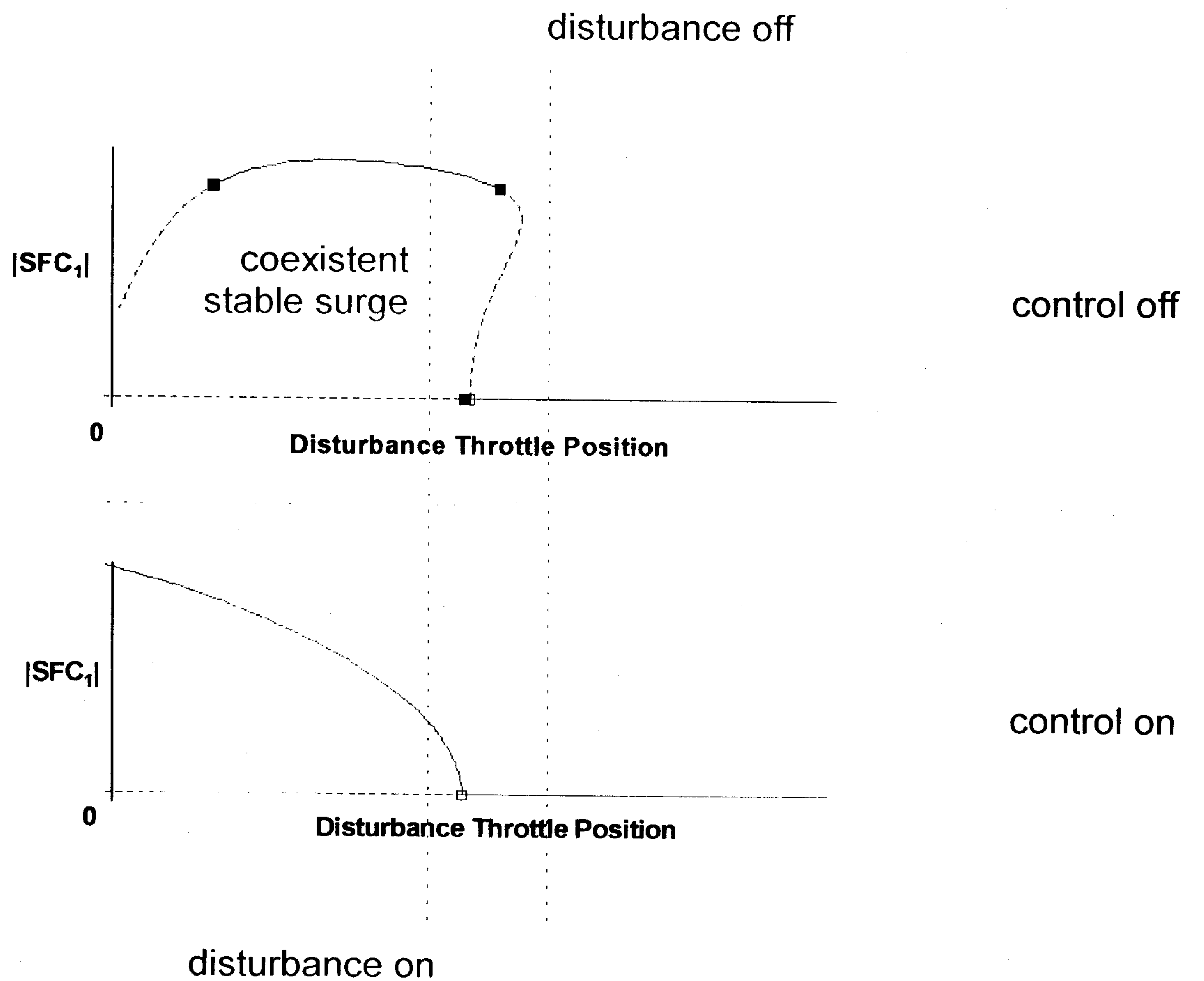
UTC Proprietary

Patent Pending

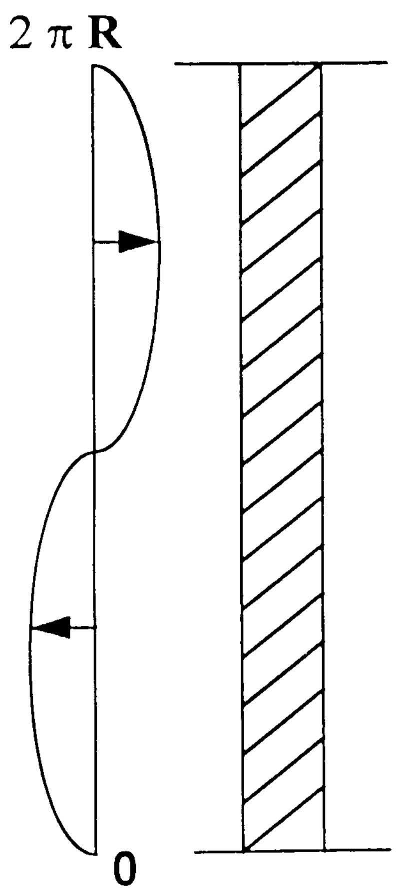
Active Rotating Stall / Surge Control Demo



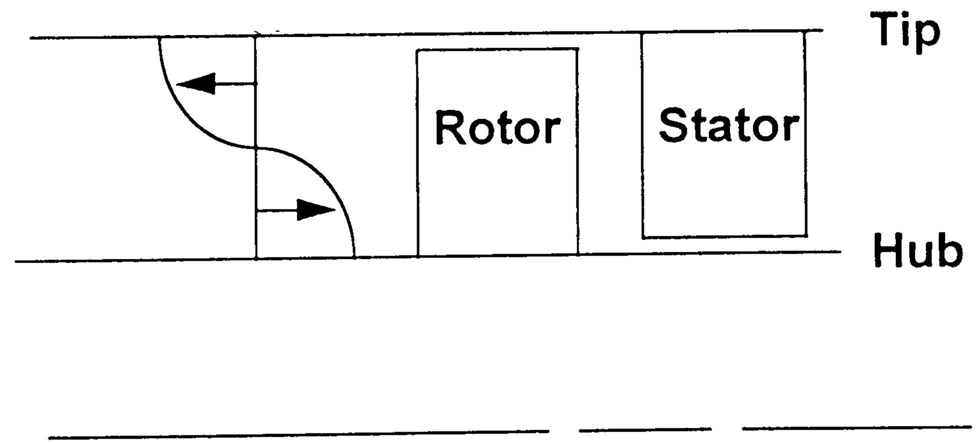
Active Rotating Stall / Surge Control Demo



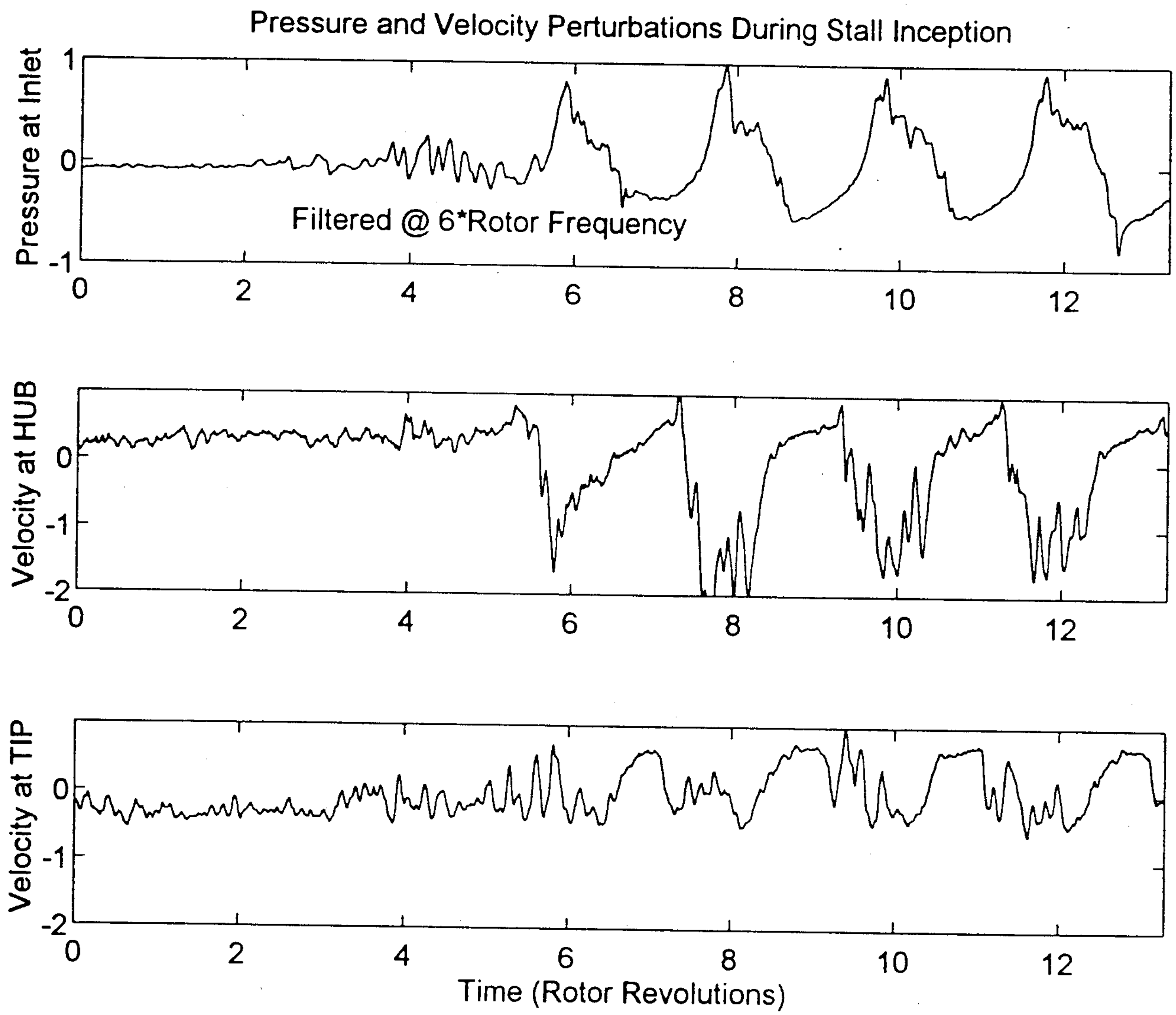
Stall Inception Models



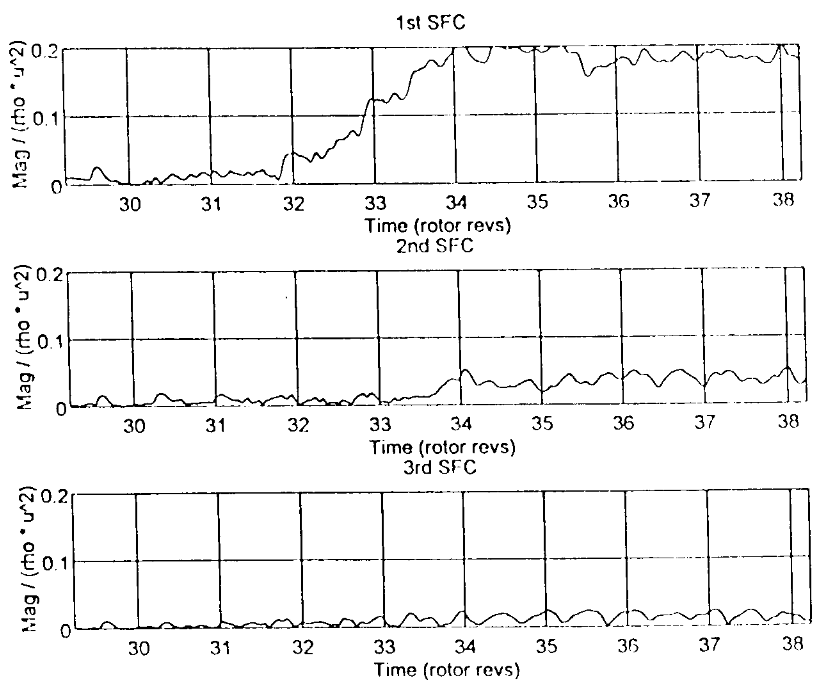
Span-wise Uniform,
Long Wavelength Inception



Part-span, Short Wavelength
Inception

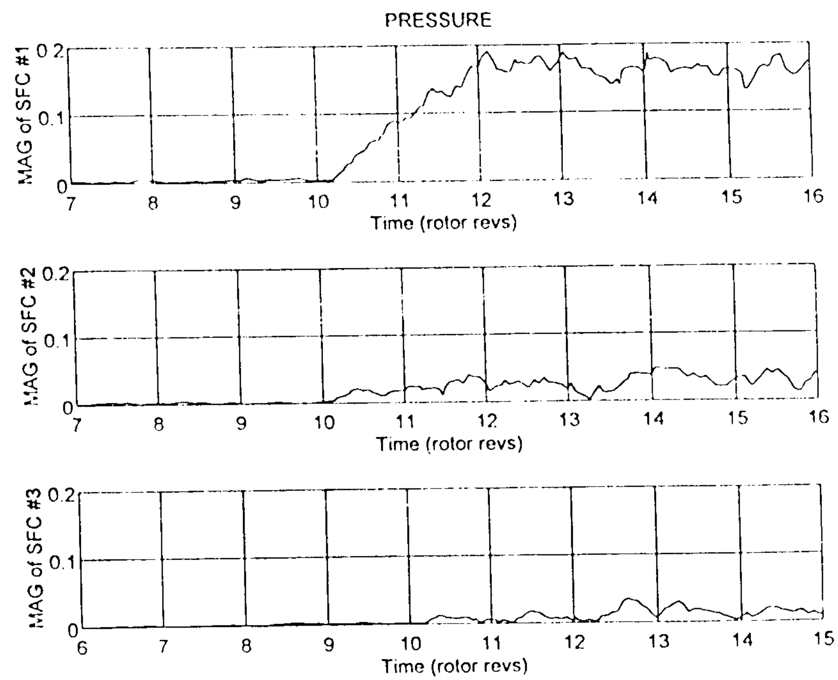

Pressure and Velocity Perturbations During Stall Inception
Pressure at Inlet
Filtered @ 6*Rotor Frequency
Velocity at HUB
Velocity at TIP
Time (Rotor Revolutions)
1
0
-1
-2
2
4
6
8
10
12

DATA

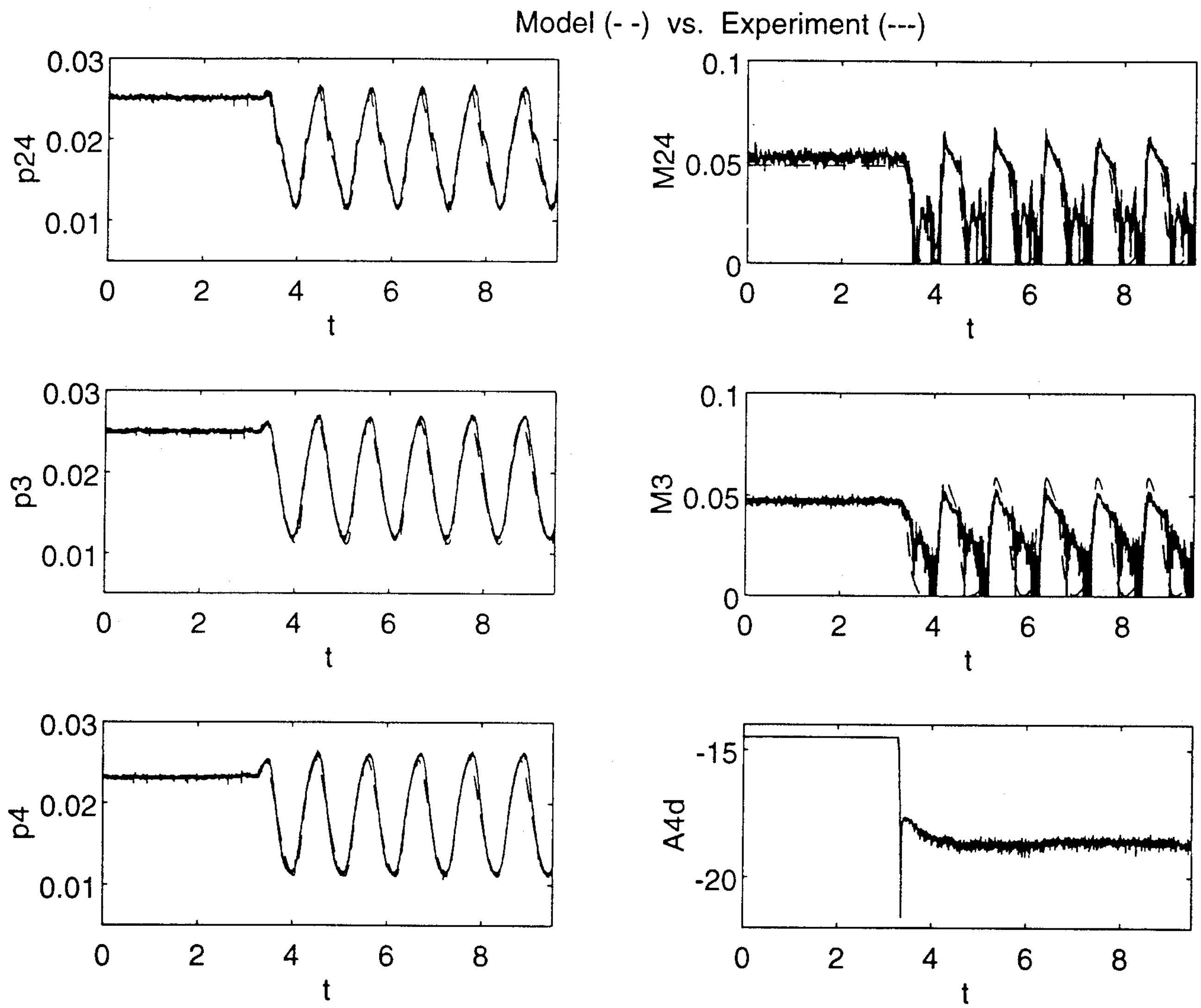


1st SFC
Mag / (rho * u^2)
0.2
0.1
0
30
31
32
33
34
35
36
37
38
Time (rotor revs)
2nd SFC
Mag / (rho * u^2)
Time (rotor revs)
3rd SFC
Mag / (rho * u^2)
Time (rotor revs)

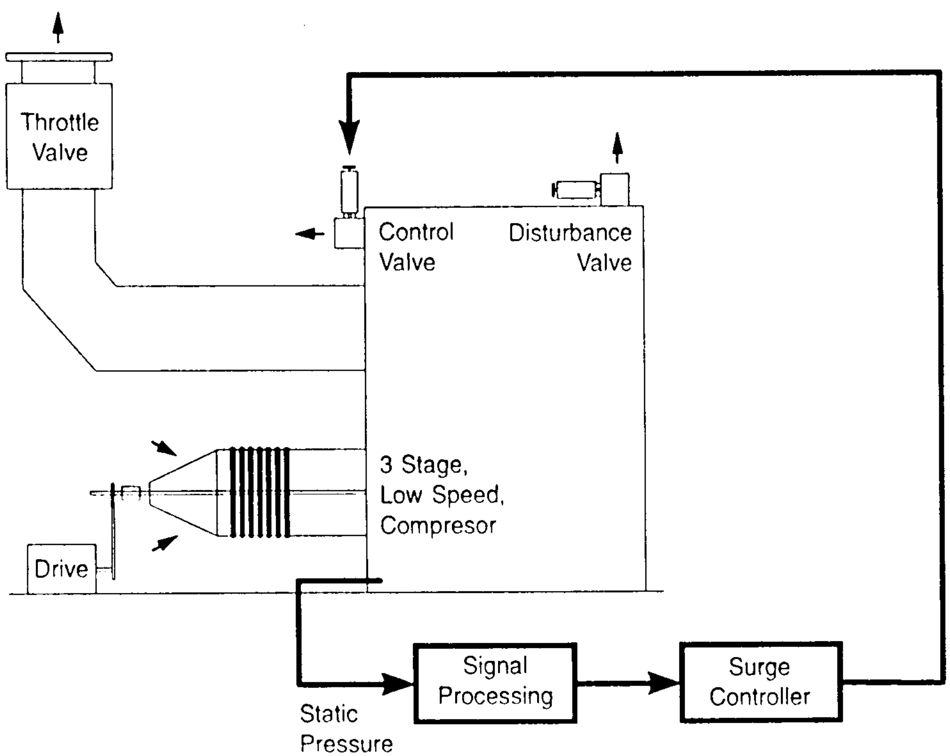
MODEL



PRESSURE
MAG of SFC #1
0.2
0.1
0
7
8
9
10
11
12
13
14
15
16
Time (rotor revs)
MAG of SFC #2
Time (rotor revs)
MAG of SFC #3
6
Time (rotor revs)


Model (- -) vs. Experiment (---)
p24
M24
p3
M3
p4
A4d
t
0.03
0.02
0.01
0.1
0.05
0
-15
-20
2
4
6
8

Model-Based Surge Controllers



Proportional Feedback Controller

	Model	Experiment
Gain Margins	+ 6.6 dB - 2.0 dB	+ 5.6 dB - 4.4 dB

Dynamic Feedback Controller

	Model	Experiment
Gain Margins	+ 7.3 dB - 4.0 dB	+ 5.5 dB - 6.3 dB

Required Extensions

Low speed to high speed (compressibility effects)

Few stage to many stage

Single spool to multiple spool

Compressors to cores to engines

Low pressure ratio to high pressure ratio

Extensions required for both models and controls

Parting Comments...

Nonlinear perspective provides a real edge

Much fruitful work can yet be accomplished in low speed environments

Carry out parallel efforts in high speed environments

Deployable hardware issues yet to be considered

A Systems Study of the Impact of Active Compressor Stabilization

3/21/94

Kevin R. Tow
General Electric Aircraft Engines
Lynn, MA.

A Systems Study of the Impact of Active Compressor Stabilization

- Overview of Assumptions
- Potential Benefits of Active Stabilization
- Engine System Level Benefits
- Aircraft System Level Benefits
- Summary of Design Options

Overview of Assumptions

- Active control provides assumed levels of additional stability margin.
- The specific method of active control is not studied.
- Potential effects of the active control hardware on efficiency or weight are not included.
- Active stabilization is used as an upgrade to both existing configurations and entirely new designs.

The systems level study assesses the bottom line benefit of having more stall margin

Advantages of Active Control Stabilization

- Current advanced control technologies are designed to <u>avoid</u> stall.

- Active stabilization suppresses the initiation of stall and increases the acceptable region of compressor operation.

- Active control has the potential for more widespread application over stall avoidance technologies.

Active stabilization includes and potentially exceeds the performance benefits of stall avoidance control technologies.

Active Control Provides Potential Benefits on Different Levels

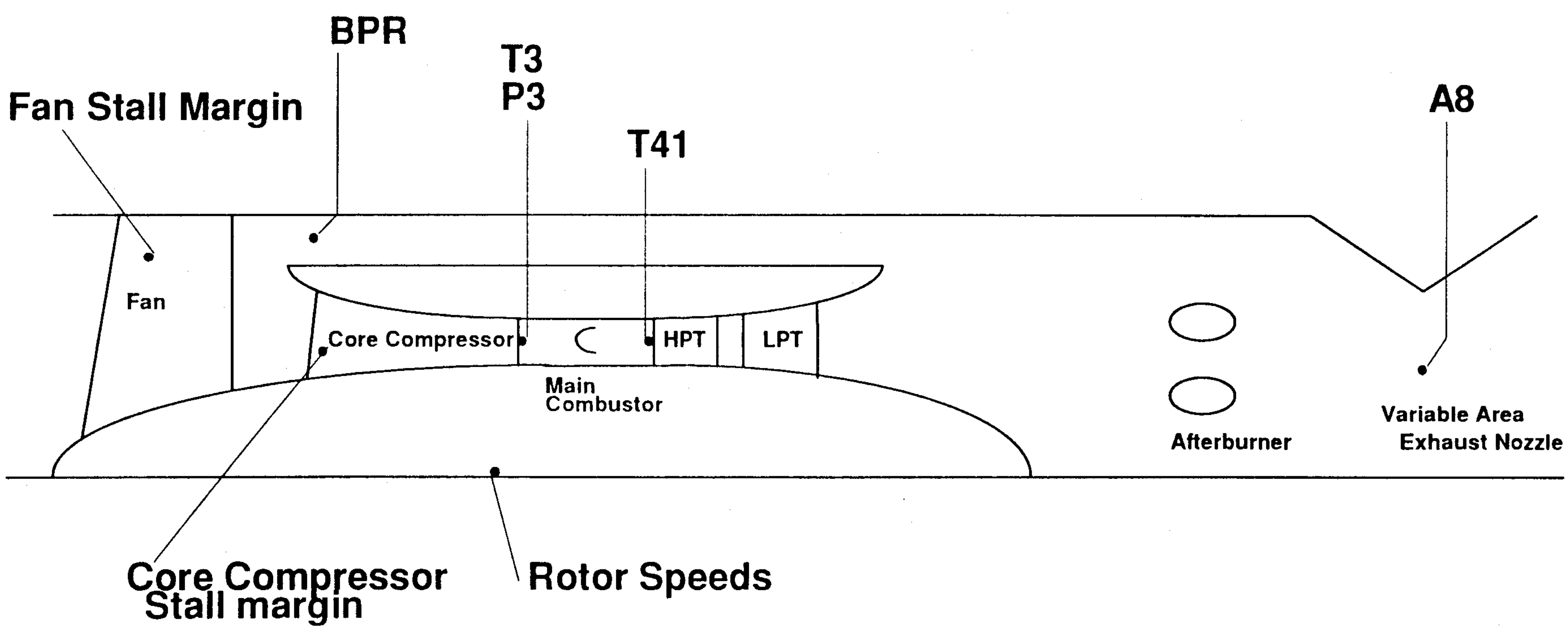
- Compressor Component Level
  - Improved adiabatic efficiency
  - Higher pressure ratio capability
  - Weight reduction
- Engine System Level
  - Improved cycle thermal efficiencies
  - Improved steady state and transient performance
  - Improved hardware durability
- Aircraft System Level
  - Improved distortion tolerance capability
  - Reduced installed drag
  - Increased aircraft range

Active Stabilization Implemented as a Retrofit Upgrade to an Existing Configuration

<u>Design Scenario</u>

- Low, bypass ratio afterburning turbofan typical for military fighter applications.
- Additional 5%-20% stall margin available
- Other cycle limits (temperatures, pressures, rotor speeds, physical geometries) remain constant

Typical Engine Design Limits

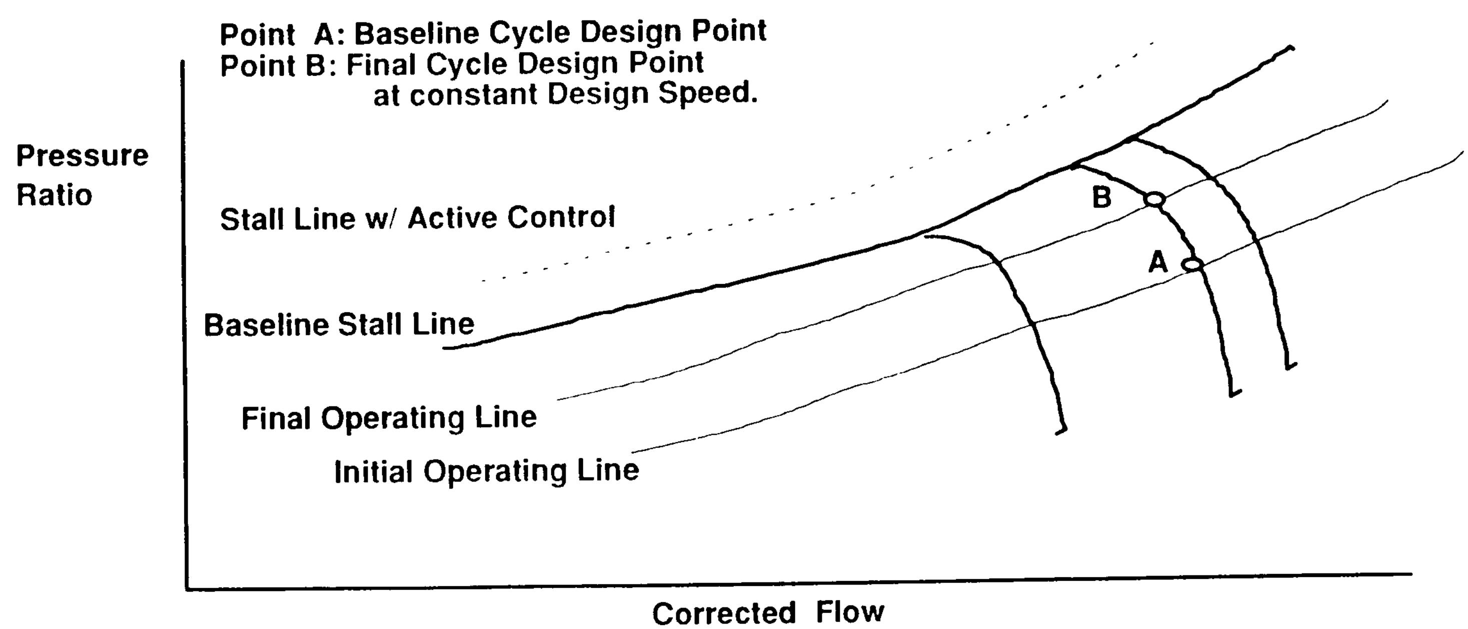


Parameters other than stall margin may limit cycle performance

Active Stabilization Implemented as a Retrofit Upgrade to an Existing Configuration

Method of Implementation

- Additional stall margin used by raising the compressor pressure ratio at constant corrected speed.
- High pressure compressor is actively controlled; the fan is not.



Active Stabilization Implemented as a Retrofit Upgrade to an Existing Configuration

Engine Performance Figures of Merit

- Specific Fuel Consumption (SFC)
  SFC= Fuel Flow/Net Thrust

- Specific Ideal Gross Thrust
  FG= (airflow)(exhaust velocity)
  FG/airflow= function (exhaust total temperature, exhaust total pressure, gas properties)

The steady state systems performance improves if the additional stall margin results in lower fuel flow, higher exhaust temperature and/or higher exhaust pressure.

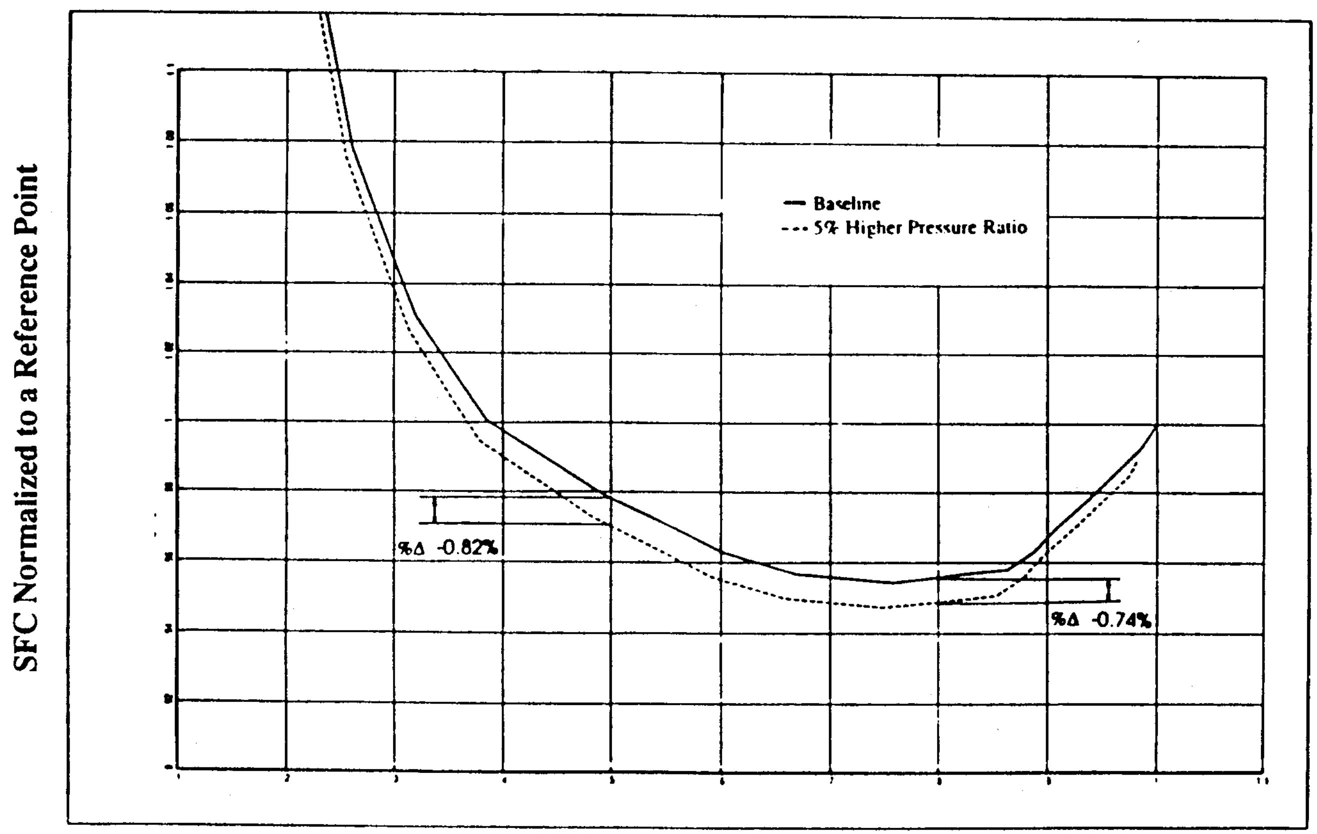
Active Stabilization Implemented as a Retrofit Upgrade to an Existing Configuration

Results

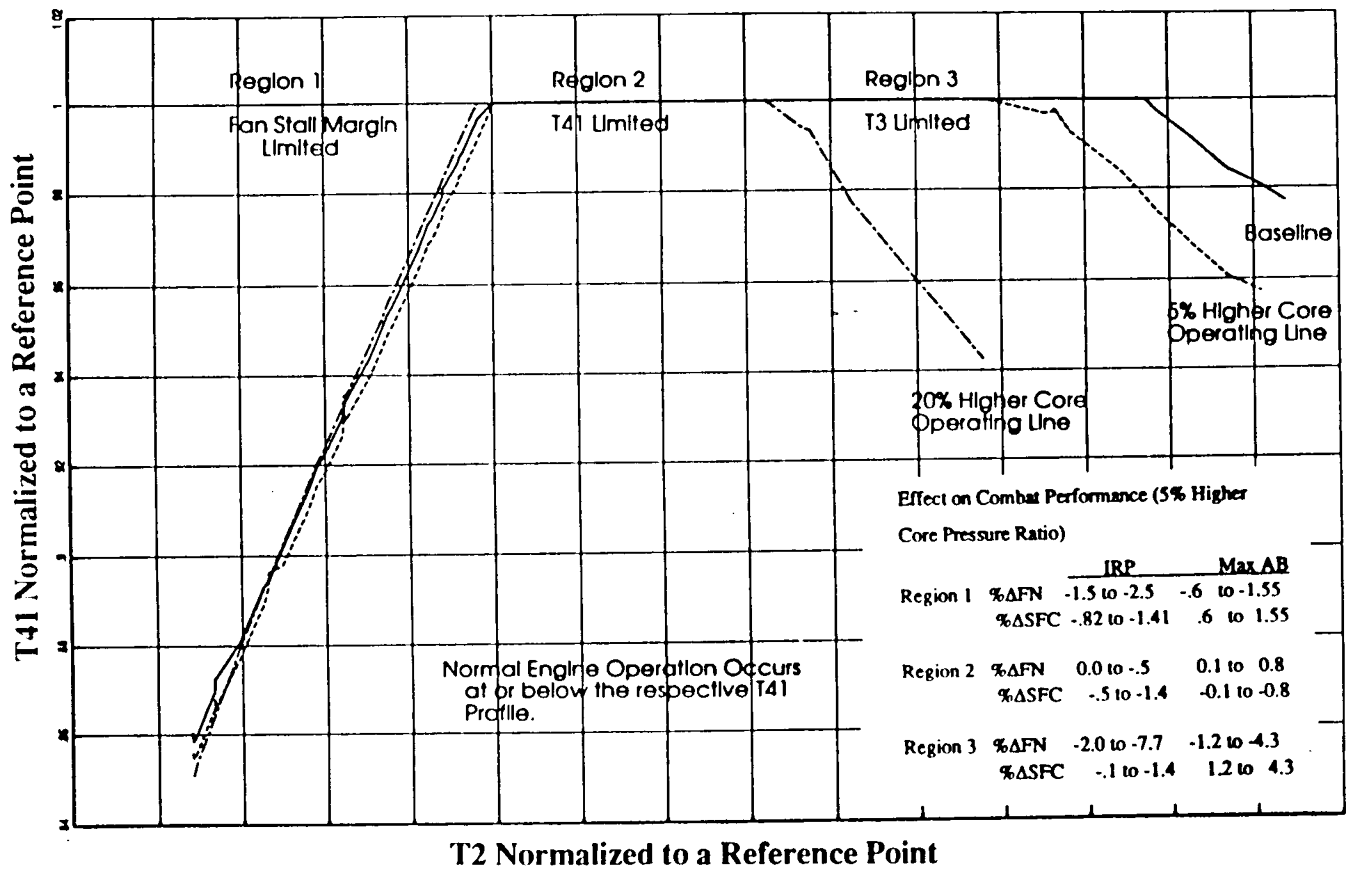
- Cruise Operation
  - Significant fuel consumption benefits
- High Power Operation
  - Higher pressure ratio results in lower turbine exhaust temperature due to temperature limits.
  - Intermediate Rated Power: thrust penalty at all flight conditions
  - Max AB: thrust benefit/penalty depending on the flight condition.

For this application, performance benefits and penalties are associated with the higher pressure ratio

Specific Fuel Consumption Benefit for Cruise Operation
35,000 ft/ .85 MN



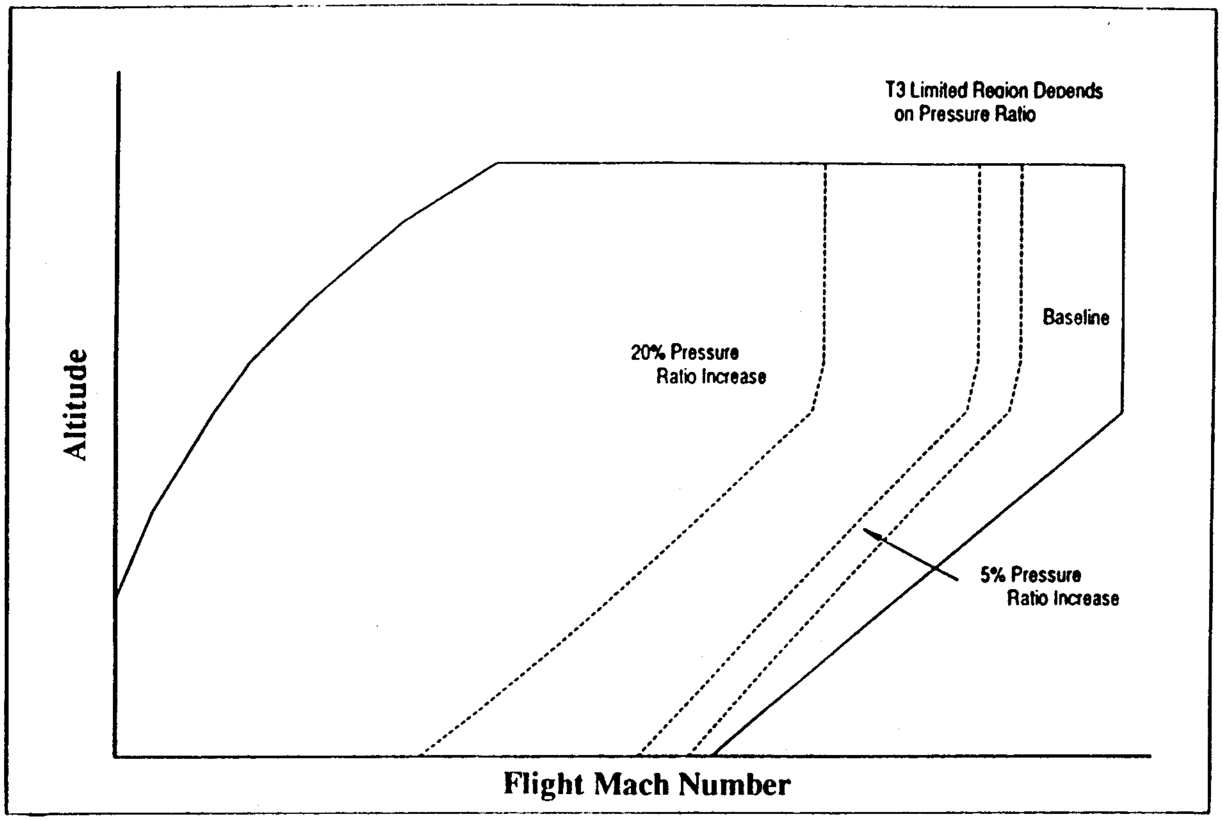
High Power Thrust Penalty Driven by Temperature Limits



		IRP	Max AB
Region 1	%ΔFN	-1.5 to -2.5	-.6 to -1.55
	%ΔSFC	-.82 to -1.41	.6 to 1.55
Region 2	%ΔFN	0.0 to -.5	0.1 to 0.8
	%ΔSFC	-.5 to -1.4	-0.1 to -0.8
Region 3	%ΔFN	-2.0 to -7.7	-1.2 to -4.3
	%ΔSFC	-.1 to -1.4	1.2 to 4.3

The presence of existing cycle constraints may compromise potential active control benefits on existing configurations.

T3 Limited Operation Covers a Larger Portion of the Flight Envelope as Core Pressure Ratio is Raised



The severity of the performance penalty depends on the location of the aircraft's critical flight conditions.

Summary of Results:
Benefits of 5% Additional Stall Margin on an Existing Configuration

- Raise core pressure ratio
  - Cruise SFC improves by -.74% to -.82%
  - Max AB thrust changes from -4.3 % to +.8% depending on the flight condition.
- Raise fan pressure ratio
  - Max AB thrust improves from 0.0 % to 5.4% depending on the flight condition.
  - No impact on cruise performance.
- Optimize efficiency using variable stators
  - Cruise SFC improves by -0.21% to -0.41%

Additional stability margin above 5% could not effectively be utilized on the existing configuration.

Active Stabilization Incorporated on a New Engine Design
(J. C. Seymour- MIT MS Thesis)

<u>Design scenario</u>

- Configuration: low bypass, mixed flow afterburning turbofan
- Implementation: higher pressure ratio operation
- 20% available stall margin

<u>Results:</u>

- 11.2% increase in mission radius
- 8.3% decrease in takeoff gross weight
- 7.3% decrease in aircraft operating weight

The benefits of 20% additional stall margin are maximized when active stabilization is incorporated early in the engine design process.

Aircraft System Benefit:
Active Stabilization on a New Aircraft Design
(Northrop)

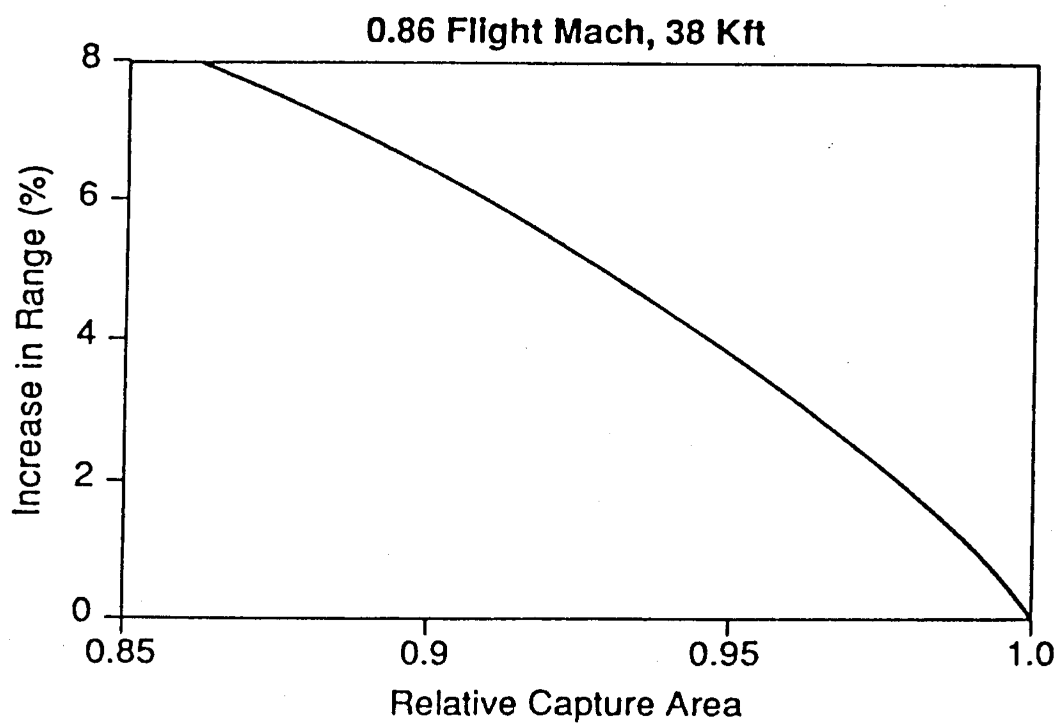
<u>Design Scenario</u>

- Configuration: high performance fighter aircraft
- Implementation: Higher compressor stall margin can accommodate larger inlet flow distortion.

<u>Results</u>

- Inlet capture area reduction
- Reduced spillage drag
- Increased aircraft range

Aircraft System Benefit: Larger Inlet Distortion Tolerance Allows Reductions in the Inlet Capture Area



The reduction in inlet area results in significant improvements in range.

Design Options for Implementing Active Control

- Performance improvements must be compared to the associated penalties. Higher stall margin capability is not simply a win-win situation.

- The presence of other cycle design constraints limits the benefits of additional stall margin on existing configurations.

- Active stabilization is likely to provide the greatest benefits on new aircraft/engine designs.

- The manner of implementation of active control is dependent on the particular aircraft application.